Chapter 3

Electron Tubes

Early fundamental work on high-vacuum tubes, which transformed the electron tube into a practical device, soon led to increased dependence on tubes in telecommunications systems and to great emphasis on higher frequencies, greater bandwidths, and enhanced reliability. In addition to extensive use in carrier transmission systems, another major use of tubes was in controlling the ringing voltage of multiparty telephones. During World War II, Bell Laboratories and Western Electric tube development and manufacture provided major support to the military effort. Early tubes for radar preamplifiers and amplifiers were designed by Bell Laboratories engineers. Reflex and magnetron oscillators also provided the key technology for radar systems. Significant magnetron advances included tunable frequencies and size and weight reductions. In the postwar period, much attention was paid to a better understanding of the physics of cathode structures, culminating in the coated powder cathode. Klystron, microwave triode, and traveling wave tube (TWT) performance was enhanced in this period, and the Telstar project capitalized on TWT advantages in one of the most dramatic communications experiments of the 1960s. Vastly increased reliability was achieved in electron tubes for submarine cable systems; the first long undersea cable system operated for 22 years under the Atlantic Ocean without a tube-related failure. Among the last electron tubes developed by Bell Laboratories were a camera tube used in the experimental PICTUREPHONE visual telephone service and memory tubes used in major experiments in electronic telephone switching.*

I. EARLY WORK ON ELECTRON TUBES

As was briefly discussed in Chapter 4, section 4.2.2 of another volume of this series subtitled *The Early Years (1875-1925)*, the application of the vacuum tube to telephony began with H. D. Arnold's recognition of the enormous potential of the crude three-electrode tube (triode) demonstrated

---

Principal authors: V. Rutter, L. Von Ohlsen, and W. Van Haste

* Registered service mark of AT&T.

to the Bell System by L. De Forest on November 1, 1912, and with the subsequent decision to purchase patent rights for the Bell System. Less than three years later, a greatly improved triode was the active device in amplifiers strung at intervals across the country, which inaugurated transcontinental telephony in January 1915. Arnold contributed greatly to this remarkable progress in vacuum tube performance by his leadership in three major types of studies: vacuum technology, cathode emission, and circuit properties.

Vacuum technology. Arnold showed that the erratic behavior of De Forest's 1912 triode was caused by poor vacuum; using better exhaust techniques, he improved conditions inside the tube envelope, with the result that triodes of a given design behaved much more reproducibly and reliably. With these tubes, practical repeaters could be designed, good enough to make possible transcontinental telephony.

(Oxide) cathode emission. Arnold studied the effect, observed by A. Wehnelt in Germany, that coating the cathode metal with alkaline earth oxides greatly increased electron emission and, with his associates, developed the combined filament using Wehnelt's discovery. This filament employed a core composed of 90- to 95-percent platinum into which 5 or 10 percent of another metal, usually iridium, nickel, and/or cobalt, was alloyed. The alkaline earth oxides were chemically combined with this core by heating to incandescence in air during the coating process. The resulting filament was, for about 12 to 15 years, the most efficient, reproducible, and rugged electron emitter known. From about 1926 to 1937, the combined filament was largely replaced in the Bell System by the uncombined type, in which the alkaline earth carbonates were applied to a base of nearly pure nickel, the carbonates being converted to oxides at an appropriate portion of the exhaust process. This change provided an uncombined coating on unipotential cathodes with nickel bases, which was less expensive than a combined coating on platinum. With improvements made in obtaining good vacuum, the more sensitive uncombined coating could be used in a wide variety of devices. (For a further discussion of cathode improvement, see section 4.1.)

Circuit properties. The behavior of the triode as a circuit element was advanced greatly by Arnold and his Bell System colleagues. This advance was based on a better understanding of the internal electrode geometry of the triode as well as of the interaction of the triode with the remainder of the circuit in which it was used.

By 1926, 15 codes of pre-1925 tubes were in manufacture at the Bell Laboratories tube shop at 395 Hudson Street in New York City. These included water-cooled power tubes for broadcasting, a small "peanut" tube for receiving (the 215A), small power tubes for public address amplifiers, and tubes for telephone repeater use. Of these last types, which were used in large numbers, the 101D was most outstanding. Figure 3-1

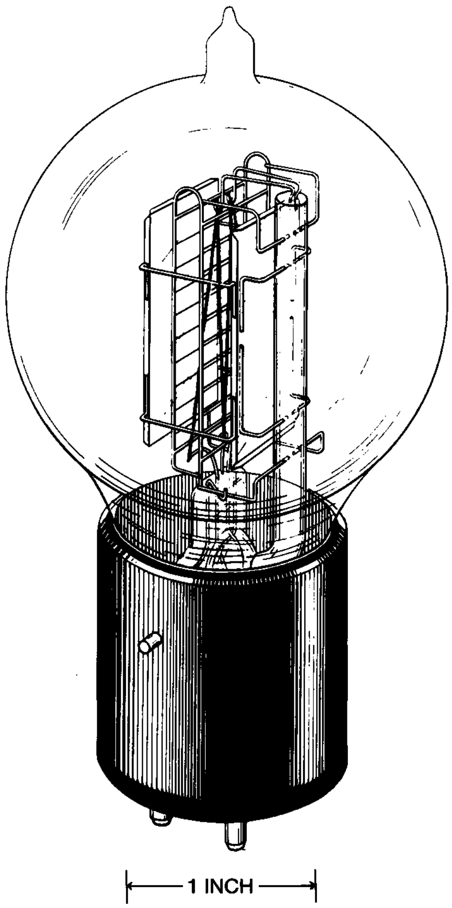


Fig. 3-1. The 101D high-vacuum triode. By 1926, when the tube had been in use for 12 years, it was the most reliable and long-lived tube ever produced. It was used in telephone repeaters.

shows its structure. It was a high-vacuum triode using a combined filament consuming 4.5 watts (W). By 1926, it had been in use for 12 years and was at that time the most reliable and long-lived tube produced anywhere. It was singled out for special comment in a 1926 *Bell Laboratories Record* article by M. J. Kelly, who was later to become president of Bell Laboratories.[1] After 1925, the 101D received many improvements in both its mechanical and filament designs. One design lowered the filament current to 1 ampere (A)—a one-third reduction from the earlier 101D. The tube was characterized by an amplification factor of 6, a plate resistance of 5700 ohms, and a plate current of 7 milliamperes (mA).

The period from 1925 to 1930 saw many accomplishments in the vacuum tube laboratory. Simultaneously, radio ("wireless") systems were being studied both at long and short wavelengths. Commercial broadcasting was expanding. All these required transmitting oscillators and amplifiers, and the Bell Laboratories group was a leader in developing these devices, in addition to developing repeater tubes for the telephone plant. It was in this period that many advanced techniques were established. Included were design and construction of high-vacuum exhaust systems, the double-ended construction techniques used for transmitting devices to limit surface leakage and to provide low-impedance electrode leads, and vastly increased understanding of the factors that affect operation lifetimes. By the end of 1930, tube lives up to 20,000 hours were being obtained with some types, and over a quarter-million tubes of all types were in operation in Bell System circuits.[2,3]

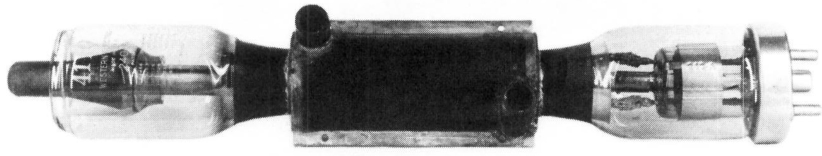
II. TELEPHONY AND BROADCASTING IN THE 1930'S

In May 1931, the Supreme Court decided that the idea of a *high*-vacuum tube, as compared with a vacuum tube, was not patentable.[4] Thus ended a 16-year controversy between General Electric and Bell Laboratories on the priority of conception of the high-vacuum tube, leaving Bell Laboratories designers with an open field for application of the tube technology. Work on a large variety of tubes was in progress, and the variety continued to expand during the next decade.

2.1 High-Power Broadcast Tubes

During this period, much attention was paid to high-frequency applications for radio-telephone circuits and to commercial AM broadcasting, and in both of these areas, power tubes were developed. Further, a considerable amount of work in aircraft, police, and marine radio was in progress, and these areas also would benefit from transmitting-tube development, especially the development of smaller, radiation-cooled devices. Water-cooled tubes continued to be needed for high-power broadcasting and transoceanic service. Figure 3-2 shows one of these devices.

The 265A, a 100-kilowatt (kW) tube developed in the early 1930s, is representative of the high-power devices of the broadcast class. For the increasingly needed low- and medium-power transmitter, which served the broadcast needs of smaller communities and was used for base station aircraft and police transmitters, a significant advance was the 1932 development of three radiation-cooled tubes, whose principal advantage was economy in circuit design. These tubes were the 270A (500 W), 251A (1500 W), and 279A (2000 W). Because the power dissipated in the tube must be lost by radiation, the anodes of these tubes used molybdenum, which ran continuously at "cherry red" temperatures. Also, fins and



|←5 INCHES→|

Fig. 3-2. The 240A water-cooled power tube. Before the development of radiation-cooled tubes, this type was used in high-power broadcasting and transoceanic service.

roughened surfaces increased the heat radiation. Molybdenum grids (carbon coated to reduce grid electron emission), thoriated tungsten filaments, and hard or Nonex*-type glass all aided in providing dependability at high operating temperatures.[5] The technical maturity of these devices was confirmed by the fact that all of these important features were still found in medium-power transmitting tubes manufactured over 50 years later.

In the mid-1930s, Bell Laboratories undertook development of a new line of high-power transmitters at the Whippany, New Jersey facility. The design was based on the Doherty linear amplifier, designed by W. H. Doherty. For a description of the amplifier and a discussion of its effect on broadcast transmitter design, see *The Early Years (1875-1925)*, p. 448.

One of the new tubes, the 298A, a 100-kW double-ended tube, was made available in the mid-1930s. This water-cooled tube had a maximum plate dissipation of 100,000 W and a maximum plate voltage of 20,000 volts (V). The anode was made of copper with an integral copper water jacket. The upper frequency limit of the tube was 20 megahertz (MHz). However, when operating under maximum power ratings, the tube was limited to 4 MHz, since radio-frequency (RF) power dissipation at higher frequencies exceeded the capability of the tube.

A new 50-kW transmitter used two of the 298A tubes. Two transmitters were made by Northern Electric from the Western Electric design and placed in service in Canada in the winter of 1937-8. The first Western Electric transmitter was installed in early 1938 in Louisville, Kentucky with the call letters WHAS.[6] There was also an interest in "super-power" 500-kW transmitters, which continued for the balance of the 1930s with the design of a 500-kW Doherty-type amplifier at the Whippany Laboratory.

Also in the latter half of the 1930s, the Bell Laboratories tube laboratory in New York City was working on a new double-ended water-cooled tube. This tube, later coded 320A, had a peak power capacity of 250 kW, the most powerful sealed-off vacuum tube ever made to that time. [Fig. 3-3]

---

* Trademark of Corning Glass Works.

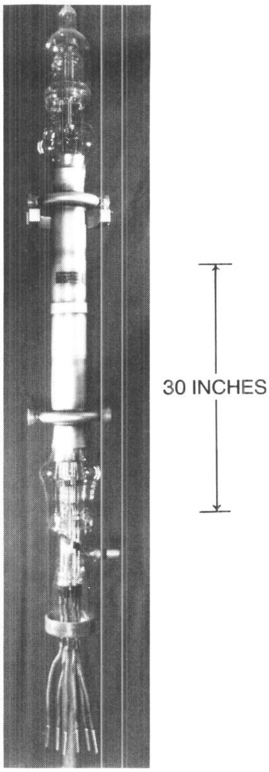


Fig. 3-3. The 320A vacuum tube, a double-ended water-cooled device. It was the first tube to use jeweled bearings or guides. Used in the 1930s for high-power broadcasting, the tube was no longer in demand after the FCC decided to limit broadcast power in the United States to 50 kW.

The size and power of the 320A presented many processing and engineering problems. When the tube was in operation, the filament strand increased in length by half an inch. The tube design had to include a tensioning device to permit expansion and at the same time keep the filament from sagging or bowing. Attached to one end of the filament strands were polished tungsten rods mounted in synthetic sapphire guides. The design eliminated the problems of seizure that resulted when metal such as molybdenum was used to guide the filament support rods during

the expansion cycle. The grid of the tube was fastened at one end and was allowed to expand in jeweled guides to accommodate changes in dimension produced by its 2000-W dissipation. This was the first use of jeweled bearings or guides in a vacuum tube.

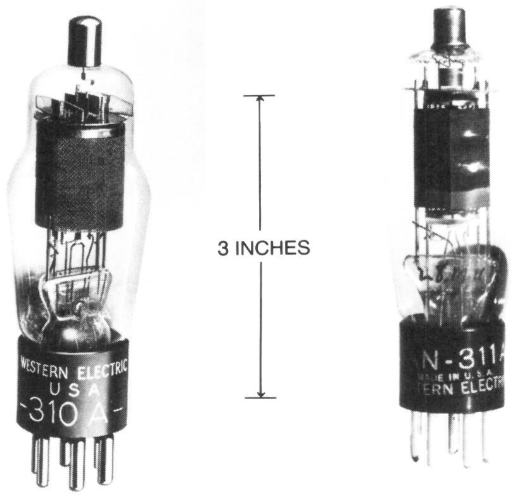
The 320A was a highly successful tube. Eight were installed (for a peak power of 2000 kW) in a 500-kW transmitter built in Mexico by Continental Electronics, an independent firm licensed by Western Electric to use the Doherty circuit. This station, XERA, operated for several years with no tube failures. The market for the 320A disappeared, however, when the Federal Communications Commission decided to limit broadcast power in the United States to 50 kW.

Shortly after World War II, Western Electric stopped manufacture of broadcast transmitters. The Western Electric tube division negotiated an agreement to transfer manufacture of their transmitting tubes to Machlett Laboratories in Connecticut. Thus, the needs of both the Bell System radiotelephone systems and commercial broadcasters were satisfied. Technical assistance from both Bell Laboratories and Western Electric was supplied to Machlett during manufacturing start-up.

2.2 The Trend to Higher Frequencies

In the receiving and telephone repeater areas, the concept of a screen grid, inserted between the control grid and anode, was well known by 1927 as a means of reducing interelectrode capacitance and thus increasing amplification at higher carrier frequencies. This tetrode concept and the pentode, with a third grid between screen grid and plate to suppress plate secondary electrons, were emphasized in the early 1930s. The climax of this work was the development, by the end of 1937, of the 310A and 311A amplifier tubes for carrier transmission systems and two companion types, 328A and 329A, designed for a different heater voltage to be used with ballast lamp current regulation.[7] [Figs. 3-4(a) and 3-4(b)] These pentode devices incorporated concepts that were to be applied in small tubes well into the era of solid state: equipotential cathodes with which an ac heater could be used, slotted mica insulators to reduce dc leakages, close electrode spacings, and shielding to reduce magnetic pickup (hum) from the heater. The extent of progress may be appreciated by comparison of the 310A pentode with the 102F filamentary triode, which was at the time the primary voice frequency amplifier in use. (See *The Early Years (1875-1925)*, pp. 844-845.) The 310A delivered a voltage gain of 44 dB, whereas the 102F delivered 26-dB gain, using similar plate voltage but usable only at much lower frequencies. The required power drive on the 310A grid was less than one-third that of the 102F.

During the early 1930s, appreciation of the broadband advantages of communication at VHF (very high frequencies—above 30 MHz) provided



(a) (b)

Fig. 3-4. Amplifier tubes for carrier transmission systems. (a) The 310A pentode offered a gain of 44 dB with less than one-third the required drive of its predecessor, which gave only 26 dB of gain. (b) The 311A pentode amplifier tube. Both designs offered equipotential cathodes, slotted mica insulators, close electrode spacing, and shielding from the heater.

a new stimulus toward the understanding and practice of the tube art. Tubes produced prior to this time would not give usable results at VHF because: (1) the cathode-to-plate transit time (the time for an electron to travel across the cathode-plate distance) was an appreciable part of the period for VHF, and (2) the shunting effects of tube interelectrode capacitance and distributed inductance could eliminate amplification at VHF. The transit-time problem in conventional tube structures can be reduced by decreasing the mechanical dimensions and using higher electrode voltages. The second problem required formulation of an electrical model (equivalent circuit) of a tube. As shown in Fig. 3-5, for a triode tube, resistance, capacitance, and inductances are present both for each electrode and between electrodes. Additionally, capacitances exist from each electrode to the outside world. As frequency of operation is increased, the deleterious effect of all these is increased. At a sufficiently high frequency, the input capacitive reactance of the grid decreases so that the input signal flows through this reactance and gain disappears. Reduction of the series resistance and inductance in each lead calls for large leads of short length. An

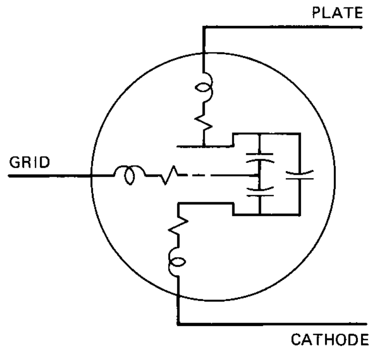


Fig. 3-5. An electrical model for a very high-frequency triode. The shunting effect of grid capacitance, the resistance, and the inductance had to be reduced.

important contribution to understanding these effects in high-frequency grid-controlled tubes was made by F. B. Llewellyn and L. C. Peterson.[8]

One of the first VHF tubes was the 304A, which could be used to amplify or oscillate at frequencies up to 350 MHz.[9] [Fig. 3-6] Note that the general construction of this tube did not depart radically from its contemporaries except that grid and plate leads were heavy and short, and both were brought out through the top of the envelope. The interelectrode capacitances were not much lower than those of contemporary tubes, but the series lead inductances were; this was the key to the tube's performance at frequencies nearly double the capabilities of others.

The next step in raising frequency occurred with elimination of the tube base, a search for ways to obtain wider spacings among the lead wires, and rearrangement of the control grid into straight wires. Such a tube, shown in Fig. 3-7(a), an experimental device only, could be operated to 740 MHz. Another tube, with further refinement, would deliver power at 1200 MHz. With these same techniques, a double-pentode negative grid amplifier was devised to deliver gain up to 300 MHz.[10] [Fig. 3-7(b)] These and similar tubes were helpful in basic work with microwaves that proved vital during World War II.

The growth of sound motion pictures required high-gain, low-noise amplifiers. Bell Laboratories efforts in this area resulted in understanding the causes of audio frequency hum arising from the heater electric field, from the heater magnetic field, and from the heater-to-output circuit because of interelectrode capacitances or direct leakage. Several tubes, such as the 259B to 262A, made quiet amplifiers that greatly benefited the motion picture industry. These tubes also served to develop methods and techniques that were later useful in the 310A and 311A for telephone repeaters.

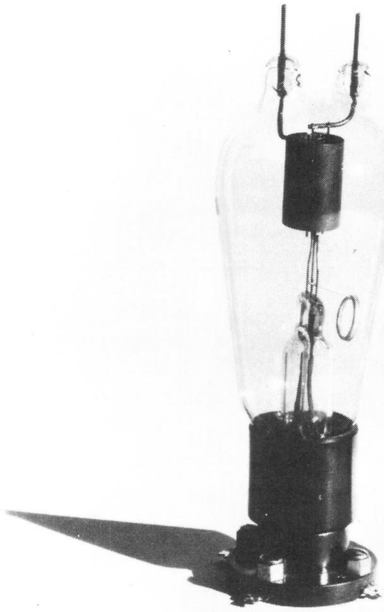
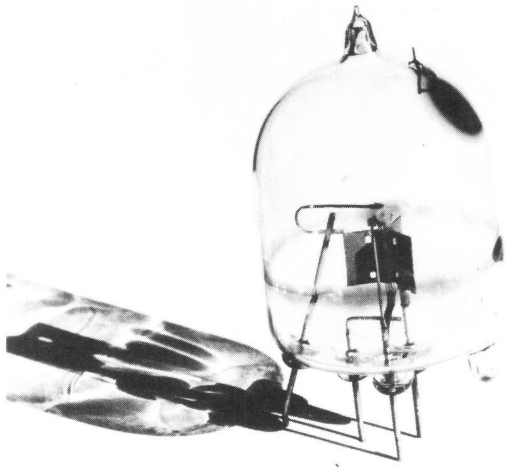


Fig. 3-6. The 304A vacuum tube, designed for frequencies up to 350 MHz. Much lower series lead inductances were the key to doubling the frequency capabilities of this device over those of its predecessors.

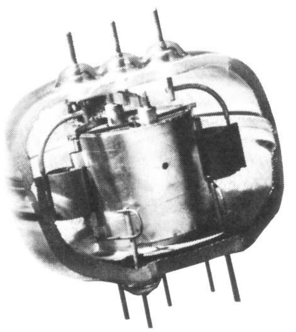
2.3 Cathode Ray Tubes

Other classes of tubes during this period included cathode ray tubes, phototubes, and gas tubes. In 1922, J. B. Johnson introduced a gas-focused, 300-V cathode ray tube for laboratory use. This tube was later extensively redesigned for production, coded series 224, with three different fluorescent screens, but from a modern perspective, performance was limited and service life was short.[11]

The next developments were an electron gun with electrostatic focusing (tubes coded 325 and 326)[12] and a tube coded 330 with three electron guns,[13] which simultaneously displayed three signal traces on the screen. The 326 and 330 tubes, shown in Fig. 3-8, were superior in performance and reliability to others available at that time, and they found a ready market.



(a)



(b)

|←— 1 INCH —→|

Fig. 3-7. Tubes representing further pre-World War II progress toward achieving high-performance VHF operation: (a) an experimental 740-MHz tube in which the base has been eliminated, and (b) a double-pentode negative grid amplifier that delivered gain at 300 MHz.

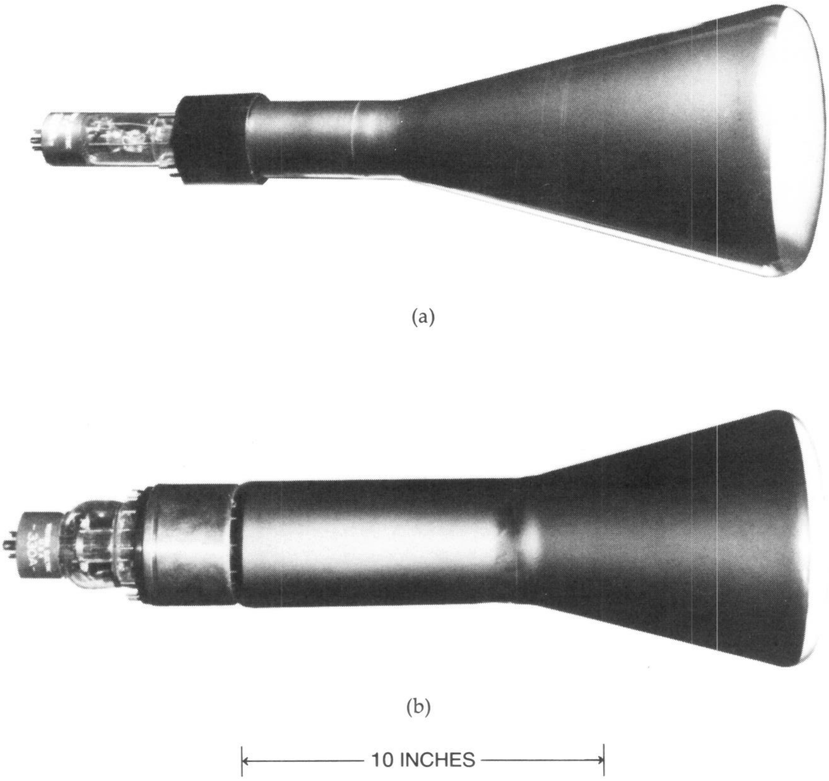


Fig. 3-8. Two Western Electric cathode ray tubes of the 1930s: (a) the 326A, which used electrostatic focusing; (b) the 330A, which had three electron guns.

An interesting project of the time was a special cathode ray tube, needed for litigation reasons, that was designed to display transient voltages on telephone lines induced from large power surges on railroad power lines. For a photographic display, both a finely focused spot on the screen and roughly a tenfold increase in electron current was achieved with a condensing lens based on a frustum of a cone that allowed the use of electrons from the entire active area of the cathode.[14]

In the mid-1920s, C. J. Davisson analyzed the focusing of electrons in fields set up in and around the apertured electrodes then in use in electron guns. Later, when the television development people were preparing for TV transmission experiments between New York City and Washington, D. C. (see *The Early Years (1875-1925)*, Chapter 7, section 9.8), Davisson was asked to design and have built a high-quality picture-receiving tube. The resulting tube was extremely long to avoid distorting the raster, and

it operated in a high-voltage, low-current mode. [Fig. 3-9] Several such tubes were built and performed excellently in a number of demonstrations.

Another special cathode ray tube was configured in such a way that the electron beam struck the side walls instead of a screen at the end of the tube. By analyzing speech according to energy at various frequencies compared to time, by tracing these quantities on the phosphorescent side walls, and by rotating the tube around its long axis, researchers were able to display "visible speech" spectrogram information continuously instead of as a series of still pictures.[15]

2.4 Phototubes

Efforts in the phototube area began in the early to mid-1920s with the need to detect light transmitted through the sound tracks of motion picture film. Initial tubes, the 1A and 2A, using potassium hydride as the photosensitive material, met with indifferent success. Developments based on

Fig. 3-9. C. J. Calbick with the picture tube designed for television demonstrations by C. J. Davisson. The tube was extremely long to avoid raster distortion.

cesium oxide/silver soon led to the superior 3A phototube, produced at the Bell Laboratories Hudson Street tube shop in New York City.[16,17] Other versions, the 5A and 6A, were developed for burglar alarms and for monitoring the recording of sound on film.

This background in phototube work led to a forerunner of the TV camera tube. In the early Bell Laboratories experiments, the subject was illuminated by a rapidly moving, scanning spot of light. In the camera, this illuminated raster was recorded on a large flat rectangular cathode. Photomultiplier tubes, some with as many as nine or ten stages, were also developed, and a special tube for extremely low light levels was built for astronomical observations.

Early in World War II, the British asked for a special, highly secret phototube, which was designed by Bell Laboratories and manufactured by Western Electric, RCA, and others.[18] Later, it was learned that this tube was put in the nose of a surface-to-air projectile. When such a projectile passed into the shadow of an aircraft's wing, the change in light level triggered a circuit that detonated an explosive charge. Postwar reports indicated that this projectile was so effective that it sharply reduced the number of German daylight bombing raids.

2.5 Gas Tubes

Hot-cathode gas tubes were used throughout industrial electronics as diode rectifiers in unregulated rectifiers, or with a control electrode, as thyratrons in regulated rectifiers. For various applications in the Bell System, several thyratrons were developed, including a unique all-metal design using mercury vapor. For high-power uses, this tube used a radiator for control of vapor pressure that provided a long life.

The cold-cathode gas tube was another type of electron tube that was given attention at Bell Laboratories and that found many uses in telephony, some leading the way to later device uses. But the cold-cathode tube used a glow discharge for conduction of current rather than the low-voltage discharge supplied by a thermionic cathode, so it could carry tens of milliamperes rather than the amperes of a thyratron. The forms familiar to industry in the 1930s were: (1) the common voltage regulator, a two-electrode device that used the spread of the glow discharge to provide a regulated voltage over a current range, and (2) another two-electrode tube designed for the discharge to provide a visual signal as an indicator lamp.

In the early 1930s, Bell Laboratories added a control electrode. A fairly well-controlled voltage on this electrode of about 70 V triggered the discharge between the main anode and cathode. The tube then became a two-state switch triggered by an isolated signal; it was used widely by Bell Laboratories in Bell System switching and relay circuits. Holding-off

voltages were on the order of 150 to 300 V in the main gap while the tube was not operating. When a tube was conducting, the voltage drop across the discharge was about 75 V, providing enough voltage and current to operate a relay, another gas tube, or other devices. Some of the features that made it attractive were (1) the lack of continual power requirements for heating a cathode, particularly in applications where the tube is not operating most of the time; (2) the isolation between the control voltage and the main gap operating voltage; (3) the stability of the firing voltage in the control gap; (4) the small size—similar to a miniature or slightly larger radio tube; and (5) the visible discharge, useful as an indicator. One disadvantage quickly recognized was that the oscillations present in the normal glow discharge interfered with the transmission of voice signals through such a tube.

Many applications were developed in the 1930s. Probably the largest was that for controlling the ringing voltage to one of four parties in multiparty telephones. By 1939, this usage was quoted as using "hundreds of thousands" of tubes,[19] and the application continued into the 1950s, when new designs were developed for mounting in telephone sets, providing extra features for ringing control in eight-party applications. The low power requirements were particularly important where the operating power for ringing a customer's telephone came from the central office. Other applications for general-purpose tubes included message registers, line identifiers, and indicators in various units of office equipment.

Early studies of the cold-cathode discharge provided an understanding of the relationship between current density and useful cathode life, so that highly reliable circuit functions could be obtained.[20]

2.6 The Design of Electron Beams

A final development is most significant. In 1940, J. R. Pierce made an outstanding contribution to the design of electron beams for cathode ray, television, klystron, and traveling wave tubes.[21,22]

Pierce's methods covered the design and shaping of auxiliary electrodes, which were connected to the cathode and grids of electron guns, and also gave the proper boundary potentials around the electron stream so that space charge repulsion would, to an excellent approximation, not expand the beam and lose electrons. The resulting beams were of uniform cross-sectional density and were far more efficient than those designed by previous methods. Pierce's methods were universally adopted, and they improved the performance of electron beams so that many additional but less revolutionary improvements became practical. (For more information on this subject, see another volume in this series subtitled *Communications Sciences (1925-1980)*, Chapter 4, section 1.1.)

III. MILITARY DEVELOPMENT DURING WORLD WAR II

Having established their capabilities in the areas of research, development, and manufacture, Bell Laboratories and Western Electric became a vital part of the tremendous World War II effort. The dimensions of military action created a need for an immense amount of communications equipment, much of it of new and complex design. The experience gained from the study of telephone tubes proved adaptable to military equipment.

One example of Bell Laboratories development capabilities and Western Electric's production experience and capacity to meet special military needs was the "three-day" design of an amplifier tube to be used in a captured German telephone system left behind as General Omar Bradley's forces advanced in Western Europe. In the retreat, the Germans had removed the tubes from the communications equipment to render it useless. However, one tube was found and sent to Bell Laboratories for urgent design effort on a replacement that would be physically and electrically equivalent. The design was completed in three days, information was given to Western Electric engineers, and in three weeks, 1000 tubes operable in the captured equipment were sent overseas to reactivate the telephone system.

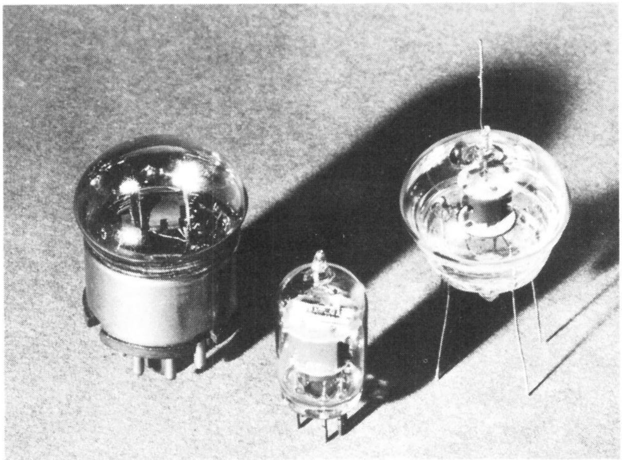
Particularly applicable was the experience accumulated over 10 years on high-frequency techniques and on radio equipment for aircraft use. The 1930s had been a decade of steady progress, with ever-lighter-weight multichannel transmitters and receivers. In the area of radar, however, Bell Laboratories had no backlog of experience, especially with respect to tubes that would meet peak or pulse transmitter power requirements of hundreds or thousands of kilowatts. Effort and ingenuity had to substitute for experience as a newly devised tube, the magnetron, was developed. (See section 3.3)

3.1 Receiving-Type Tubes

Military requirements for general-purpose tubes are closer to requirements for Bell System use than to those of the entertainment or industrial fields. These are a long life (although the military always had to be ready to sacrifice long life for high performance), ruggedness, high transconductance, low noise, and high input impedance. By 1941, the 386A and 717A represented the latest thinking on high-gain and high-figure-of-merit tubes for use in the telephone plant. The 717A pentode and the 6AC7 commercial pentode became the first tubes used in preamplifiers and intermediate amplifiers used in radar. Intermediate-frequency (IF) amplifiers using the 717A had a gain of 85 dB at center frequencies of 30 and 60 MHz and a bandwidth of 4 MHz, with a weight of just under two pounds. A large part of the Western Electric-manufactured airborne bomb-

ing radar equipment used this amplifier, with few additional changes as time progressed.

The search for more compact and lightweight amplifiers resulted in the famous 6AK5 pentode,[23] which delivers gain of approximately the product of grid plate transconductance (g_m) and the load resistance. In the case of the triode, the gain is not this high, because the effective load resistance is shunted by the tube plate resistance, which in a triode is usually lower than, or comparable to, the load resistance. The 6AK5, with plate voltage of 250 V, yields g_m of 5000 microsiemens (mS) and may be compared with the World War I "peanut" tube of much the same size, which yielded a g_m of 420 mS. The 6AK5 thus represented a major improvement over earlier small tubes. Figure 3-10 shows the 6AK5 with its immediate predecessors, the 717A and the 386A. A companion of this tube, the 6AJ5, was developed for use in aircraft equipment, at plate and screen voltages of 25 to 30 V. The lower voltages were necessary because of the limitations of aircraft power supplies. The 6AJ5 was a lower-g_m tube, of about 2000 mS, but it served well as an airborne IF amplifier. The major developments in such tubes included the oxide-coated cathode, a flat glass plate through which connecting pins were sealed, direct mounting of the tube structure on these pins with short leads (low inductance), and small elements mounted on low-leakage coated mica supports. As a result, high gain to at least 100 MHz could be achieved.



|← 1 INCH →|

Fig. 3-10. The famous 6AK5 pentode (center), a major improvement over its immediate predecessors, the 717A (left) and the 386A (right). It remained for decades the standard for moderate- to high-performance, low- and medium-frequency tubes.

The basic structural features of the 6AK5 increasingly became the standard for moderate- to high-performance, low- and medium-frequency tubes, and remained so for decades; the major change after World War II was the inclusion of more than one tube within a single envelope. One of the first of these modern multifunction devices was the Western Electric 396A, with two entirely separate triodes in the same envelope.[24] However, one even earlier Western Electric development, the 292A/303A, performed multiple functions with a common cathode.

3.2 Reflex Oscillators

A major need early in the war was for a source of local oscillator signals at centimeter wavelengths to be used in radar systems. The need arose because no sufficiently low-noise detectors were available to allow direct rectification at ultrahigh frequency (UHF) or microwave frequencies. Further, detection at the incoming frequency would result in loss of selectivity, so it was necessary to heterodyne down (or "beat" down) the reflected radar pulse and amplify at a lower frequency of 30 to 70 MHz. Because available mixers would yield an optimum signal-to-noise ratio over a very narrow range of beating signal power, the general need was for beat oscillator power on the order of 20 milliwatts (mW).

Soon after the invention of the klystron by the Varian brothers[25] at Stanford University became generally known, Pierce and W. G. Shepherd of Bell Laboratories invented the reflex klystron oscillator[26] (see *Communications Sciences (1925-1980)*, Chapter 4, section 1.2). This microwave oscillator played a particularly important role in radar. Because of the need to stay near to, but separated by the IF from the incoming pulse frequency, the reflex oscillator needed to be stable and, ideally, follow variations in transmitter frequency automatically. Much of the rapid improvement of the performance of this oscillator to meet specific requirements came from Bell Laboratories efforts.

The reflex oscillator extends the frequency range far beyond that of a gridded triode or pentode, where performance deteriorates at higher frequencies and where electron transit time from cathode to plate is a significant fraction of the period of oscillation. In the reflex klystron, the electron beam is bunched—i.e., velocity modulated—by the RF electric field of the resonant cavity of the tube structure. A schematic cross section of a reflex oscillator is shown in Fig. 3-11. Dimensions are such that C, a round, pillbox-shaped cavity, and the grids that cross two holes within the cavity, are self-resonant at a desired microwave frequency. Electrons emitted from a hot cathode K are accelerated toward and through the grids by a positive potential on the cavity. The repeller R is operated at a negative voltage with respect to the cathode. Upon proper adjustment of voltages of the retarding field, the bunched electrons can be made to

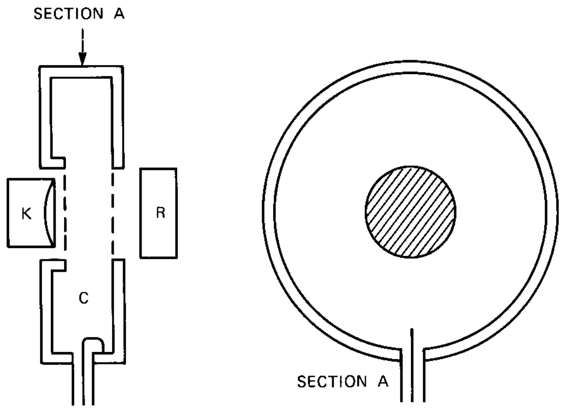


Fig. 3-11. Schematic of a reflex oscillator. Hot cathode K emits electrons through grids toward repeller R. Dimensions are such that cavity C and the grids are self-resonant at the desired microwave frequency.

traverse the grid structure in the correct phase to give up energy to the circuit. The tube oscillates, and RF power is delivered to an external microwave circuit coupled to the cavity. The advantages of the klystron are that it is basically a high-frequency device; it is compact and requires only moderate voltages; it does not require an external beam focus arrangement; and, importantly, it can be tuned over an appreciable frequency range by merely changing repeller voltage. Thus, it can be a tunable microwave source or, as later used, it can be frequency modulated by coherent information impressed on the repeller voltage. A primary problem with the device is its low overall efficiency of only a few percent. This limitation, however, is not very important in local oscillator use, where only a few milliwatts of power is required.

The cavity of the reflex klystron can be either external or internal to the vacuum envelope. The Western Electric 707A was the first reflex klystron to be extensively used in a radar application; it had an external cavity. The tube, which can be seen in Fig. 3-12, used two Houskeeper seals of copper to glass (see *The Early Years (1875-1925)*, p. 849). These early seals were also the cavity contacts.

The 707A operated at 3 gigahertz (GHz) and was the first reflex oscillator to be designed for voltages as low as 300 V, an advantage in the design of radar equipment, because the oscillator can be driven from the low-voltage supply that powers IF amplifiers, preamplifiers, etc. The use of fine mesh wire grids instead of coarse wire or no grids increased the efficiency of beam bunching and increased the range of electronic tuning.

For extension to higher frequencies, and for a compact manufacturable structure, the tuning cavity needs to be integrated with the electronic array.

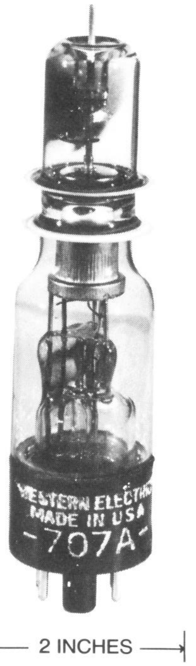


Fig. 3-12. The 707A, the first reflex klystron designed for voltages as low as 300 V, an advantage for radar equipment.

The basic design that resulted, after the usual development problems, was typified by the 2K25, a 10-GHz oscillator, shown in Fig. 3-13. While the 707A set the precedent in voltage range, the 2K25 became the prototype for the mechanical configuration of later oscillators. From the figure, it can be seen that the outer shell, plus added grid supports, form the resonant cavity. The base is standard octal, and the coupling loop is part of a coaxial line that, at the base end, can be inserted parallel to the electric field lines in a waveguide operating in the TE_{10} mode.

Mechanical tuning was needed so that the center frequency for any electronic tuning could be varied. This was achieved, but with considerable difficulty. For adequate control, it is necessary to set grid spacing reproducibly to a few millionths of an inch, without backlash. This was finally accomplished by the mechanism shown in Fig. 3-13 and described in principle by Fig. 3-14. Turning the threaded screw varies the overall length of the bow arrangement by extremely small increments. The screw threads into a nut in each bow, one of which has a right-handed thread, the other, a left-handed one. By coupling to one grid, the mechanical spacing between grids is varied.

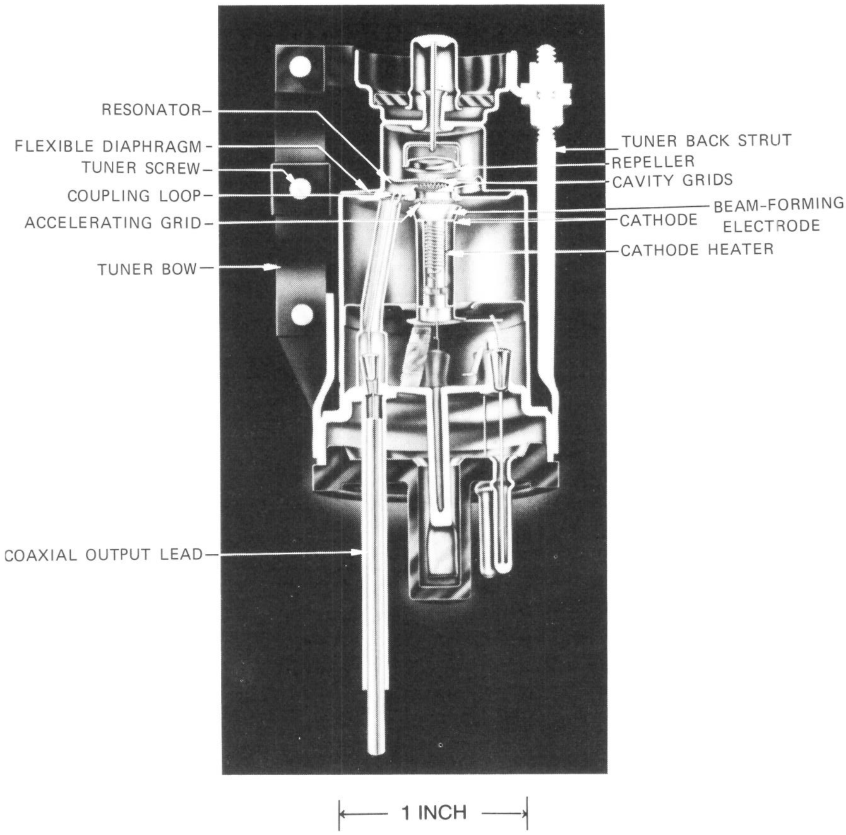


Fig. 3-13. Internal structure of the 2K25 10-GHz oscillator tube, in which the tuning cavity was integrated with the electronic elements to form a compact structure.

Additional changes in the 2K25 type of device were made to satisfy military requests for plug-in replacement—i.e., interchangeability. These included changes to the electron gun and repeller shapes to eliminate discontinuities in output, and improvement to the tube-waveguide match.

Perhaps the last major contribution by Bell Laboratories to the reflex klystron during World War II was the development of thermally tuned tubes. The need for such tuning arose from the desirability of reducing adjustments in the radar systems to a minimum, and the need to cope with the possibility of enemy jamming. The latter problem, in particular, dictated the need for fast frequency change; both transmitter and receiver would have to be changed by the same interval. The reflex oscillator requirement was for a tuning range greater than 1000 MHz.

The first tube of this type made in quantity, the 2K45, employed a triode built into the reflex oscillator envelope in a way such that the anode,

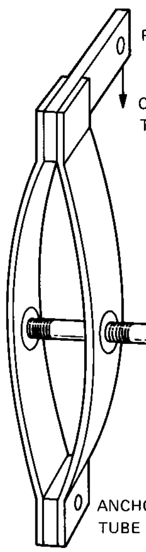


Fig. 3-14. Mechanical tuner for the reflex oscillator. This component allowed reproducible grid spacings set to a few millionths of an inch for variable electronic tuning.

a channel-shaped member, is an element with a high coefficient of thermal expansion. Welded to this at the ends is a bow of low thermal expansivity material. Incoming electron current heats the anode, which then expands, causing the bow center to move toward the anode. The bow is coupled mechanically to a cavity grid, thus effecting spacing change. The construction is illustrated by Fig. 3-15.

The 2K45 also was the first major design to use an electron gun of spherical rather than cylindrical geometry. The spherical gun eliminated output discontinuities and a gun grid, and lowered grid losses in the interaction space.

During World War II, device people in industrial, university, and government laboratories cooperated effectively. V. Neher of the Massachusetts Institute of Technology Radiation Laboratory had been working on a model of a UHF klystron that could be manufactured in quantity. Neher approached Bell Laboratories to develop a design for possible manufacture by Western Electric and/or other manufacturers.

As a result of this interaction, the 2K50 klystron oscillator was developed at Bell Laboratories by the J. O. McNally-V. L. Ronci klystron groups. The tube, with an upper frequency of 25 GHz, had a resonant circuit and a means of tuning in an integral package. Tuning was accomplished thermally

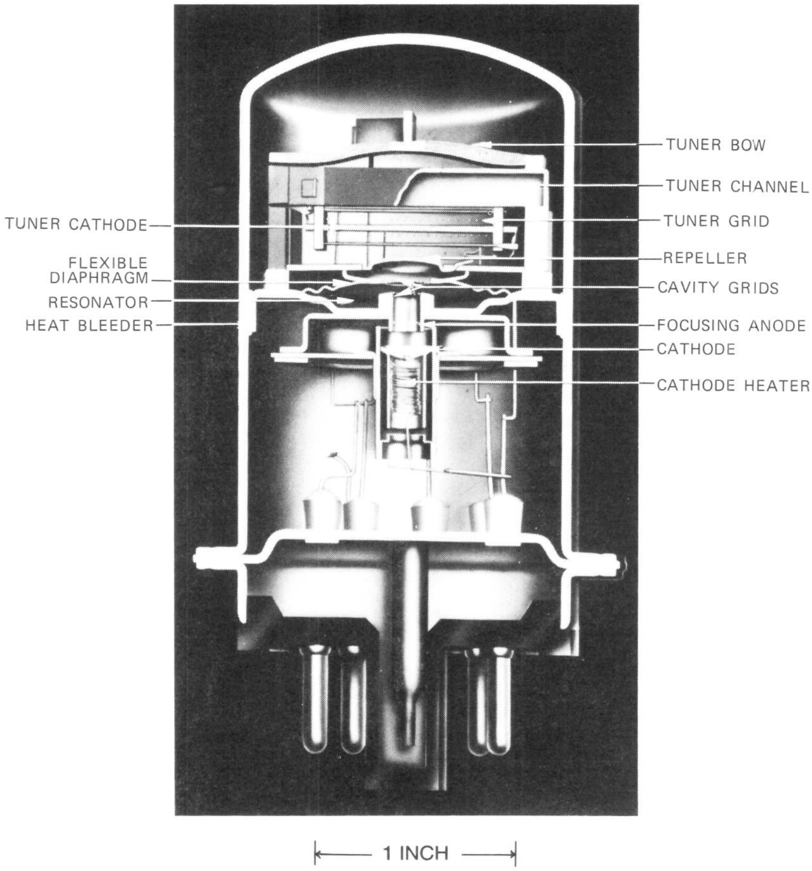


Fig. 3-15. Construction details of the 2K45 klystron, a thermally tuned tube for radar applications. Temperature changes in elements at the top changed cavity grid spacing and thus the operating frequency.

and controlled by a triode section in the tube. The tube output was delivered through a window rather than a coaxial lead as in older reflex oscillators. It was designed for direct coupling to a waveguide by a plastic connector. A slot in the connector was used to orient the waveguide with the waveguide section of the tube. Because of the end of World War II, the 2K50 was not manufactured by Western Electric.

In all, a great variety of oscillators were developed for military use. One design with the 2K45 was used in a pulse position modulation system for communication. A measure of the merit of Western Electric tubes is that of eleven Army-Navy preferred types, nine were of Bell Laboratories design. Figure 3-16 shows a list of the devices plotted against frequency.

Further expansion of the uses of the klystron would come about with its application as a power output tube in microwave radio relay systems as the decade closed.

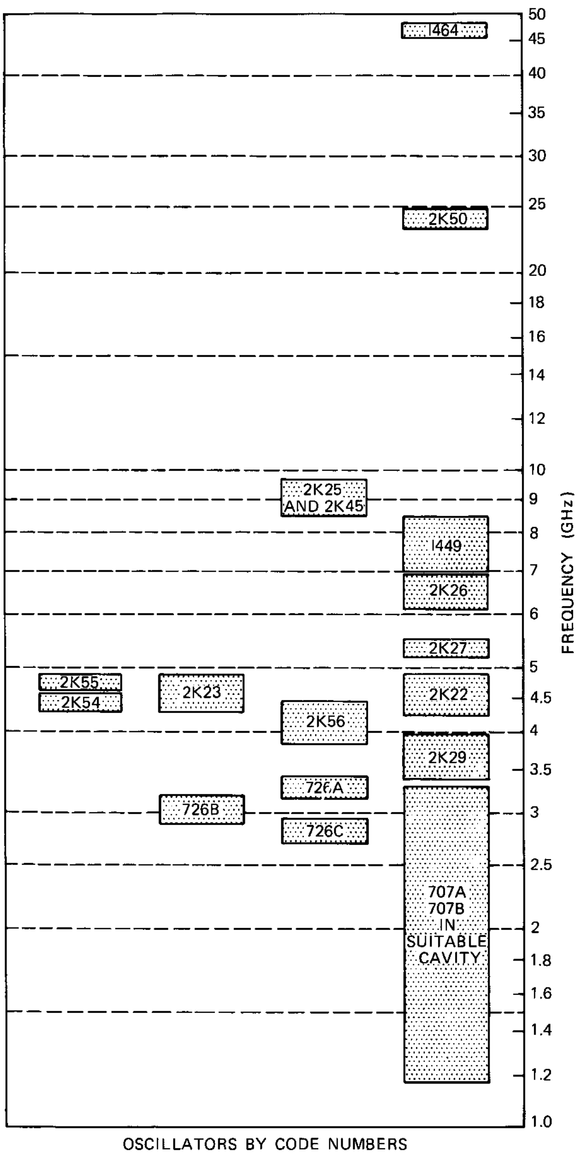


Fig. 3-16. Reflex oscillators designed at Bell Laboratories for military use, plotted against frequency.

3.3 Magnetrons

Probably no single development of the electron tube art of the period was as crucial to the outcome of the war as the resonant cavity magnetron oscillator. Without this oscillator, there was no way of reliably generating centimeter wavelength pulse power in the high-kilowatt and megawatt range, a range needed for effective application of radar over usable distances under all conditions of atmospheric water vapor content. Previous to 1940, radar development was being conducted by use of triode tubes that would, at best, deliver only a few kilowatts of microwave pulse power.[27] In 1940, however, an early British magnetron was brought to Bell Laboratories for study, and it was immediately apparent that a breakthrough in the power-frequency limitation had been found. The British device was reproduced in the Bell Laboratories tube shop at West Street in New York City, and from that point, a continuously accelerating research and development program began. This resulted in major contributions by J. B. Fisk, P. L. Hartman, H. D. Hagstrum, and others at Bell Laboratories (see *Communications Sciences (1925-1980)*, Chapter 4, section 2.1). At first, Bell Laboratories carried nearly the entire development load for the United States; later, the Massachusetts Institute of Technology Radiation Laboratory shared the responsibility.

The operation of a multicavity magnetron oscillator is more difficult to explain than the operation of most tube types. The basic requirement is that electrons emitted from a cathode, and drawn toward an anode, be bunched in some way to give up energy to an RF field existing in a resonator system. This requirement is identical to that for a reflex oscillator, as previously described. However, in the magnetron oscillator, a magnetic field is introduced at right angles to the dc electric field. In this crossed electric-magnetic field, individual electron motion becomes cycloidal, and the average path length before interception by the anode is greatly extended. The corresponding interaction path length is also extended, leading to the possibility of efficient energy transfer from electrons to the resonator RF field.

Figure 3-17 shows the basic parts of a magnetron oscillator for centimeter wavelength RF generation. The multicavity resonator anode consists of six or more individual resonators, each consisting of the hole and an entrance slot to the hole. Each individual resonator is coupled to its neighbors. Coaxially mounted inside the resonator is a cylindrical cathode. The space between cathode and resonator is the electron interaction space, where electrons become bunched in proper phase to yield net energy to the resonators as they pass each slot. Not shown is the magnetic field, applied vertically through the structure. In typical radar operation, a control circuit applies a high positive voltage (with respect to the cathode) to the anode in short pulses; peak pulse currents may reach many tens of amperes.

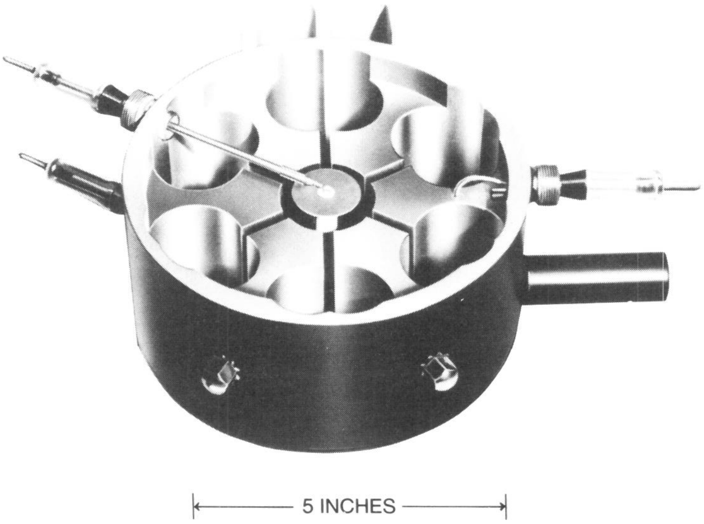


Fig. 3-17. Basic structure of magnetron oscillator for centimeter wavelength RF generation. A series of resonators with radial slots surrounds a central cylindrical cathode.

The multicavity arrangement is closed upon itself, and therefore self-exciting, so that oscillation occurs during the pulse, the frequency being determined by the dimensions and configuration of the resonator structure.

The multicavity structure of the device allows different modes of oscillation, and therefore different frequencies. A primary problem with magnetron design, and this was the case in 1940, is how to provide a clean single-frequency output. An important objective was to widen separations between operating frequency and undesired modes. This objective was accomplished by alterations to the resonator structure. Two methods were used. In the first, which was applied to 10-cm and 3-cm magnetrons, coupling between resonators was increased by strapping, i.e., the tying of alternate anode segments, at the capacitance part of the resonators, with wire straps at each end of the anode block. Since the efficient mode operation was the π mode, in which alternate anode segments are 180 degrees out of phase, the straps would not adversely affect the operation in this mode but would tend to disturb the other competing modes. In the second method of anode design, alternate cavities, made of simple wedge-shaped resonators, were of different lengths. The π mode frequency was situated in a large gap in the mode spectrum, approximately midway between the frequency associated with the small resonators and that corresponding to the large resonators. This design was particularly good for 1-cm and shorter-wavelength magnetrons, where strapping would be extremely difficult.

(See another volume in this series subtitled *National Service in War and Peace (1925-1975)*, Chapter 2, section IV.)

The first magnetron designs produced, the 700A to 700D, employed techniques similar to those used to produce the original British device. These units were for a 40-cm wavelength and necessarily departed considerably from the dimensions of the British model, which operated at 10 cm. Initial models were not strapped, but when strapping was introduced, the efficiency was increased to the level of later devices—as high as 60 percent. The 700 series was applied to advantage in early radar for controlling guns on naval ships.

Resonator strapping was used in immediately succeeding designs, the 728 series and the 5J23. In this period, the noncontacting coaxial load-coupling scheme was devised; this is a means of reflecting, by a slot one-half-wavelength long, a metallic short circuit to the point where the coaxial line and the magnetron loop pickup line meet. Such a joint eased the requirements on the glass seal across the coaxial output of the magnetron.

When a new frequency allocation required redesign of several magnetrons, it was possible to predict performance by previously accumulated knowledge of the effect of design parameters, and the results of mechanical scaling had reached the point where effects on performance could be predicted. The 4J21 to 4J30, for the 20- to 30-cm band, were designed and built in a reasonably straightforward manner. They used a double-ring-strapping arrangement with fine frequency control being attained by strap size variation. The contact-free, or choke, coupling was used. A pulse-power output of 750 kW at 50-percent efficiency was obtained.

As frequency of devices was increased, it became preferable to have power coupled directly to a waveguide. This required development of a coaxial-to-waveguide transition, adaptable to a given design. A more direct way of coupling the magnetron power to the external waveguide was devised and first used in K-band magnetrons by S. Millman at the Columbia Radiation Laboratory.[28] In this design, a low-impedance, quarter-wave slot transformer connects the back of one of the magnetron resonator sectors to a short section of K-band waveguide inside the vacuum envelope. A properly designed circular glass window in a Kovar* cup, isolated by choke joints, provides the vacuum seal. This design was adapted to 3-cm magnetrons by using a quarter-wave transformer of H-shaped cross section. (See *National Service in War and Peace (1925-1975)*, p. 121.)

For the same reasons noted in the discussion of reflex oscillators, tunable frequency became an early goal. Work on tuning followed the course of operating on a single resonator and of tuning all resonators simultaneously.

* Trademark of Carpenter Technology Corp.

The former can be achieved by coupling to the outside and then varying the impedance outside the cavity. This asymmetrical tuning scheme does not result in a wide tuning range, and moding (i.e., shifting of operation to an undesired frequency) is difficult to avoid. It was found that the most acceptable arrangement is to provide a means of varying capacitance to resonator straps. A vacuum diaphragm is then needed to attain smoothly controllable movement of pins inserted into each resonator within the envelope. Figure 3-18 shows this arrangement as it was incorporated into the 4J51 tube.

With the introduction of strapping and tuning methods, the basic magnetron techniques were available, and a great variety of devices in various power and frequency ranges were designed and manufactured. A further mechanical simplification was made, however, by producing a packaged tube, i.e., one in which the external magnet was an integral part of the device. Magnet weight and size could thereby be reduced significantly. A photograph of the 2J55, the packaged version of one of the most extensively manufactured designs (725A), is shown in Fig. 3-19.

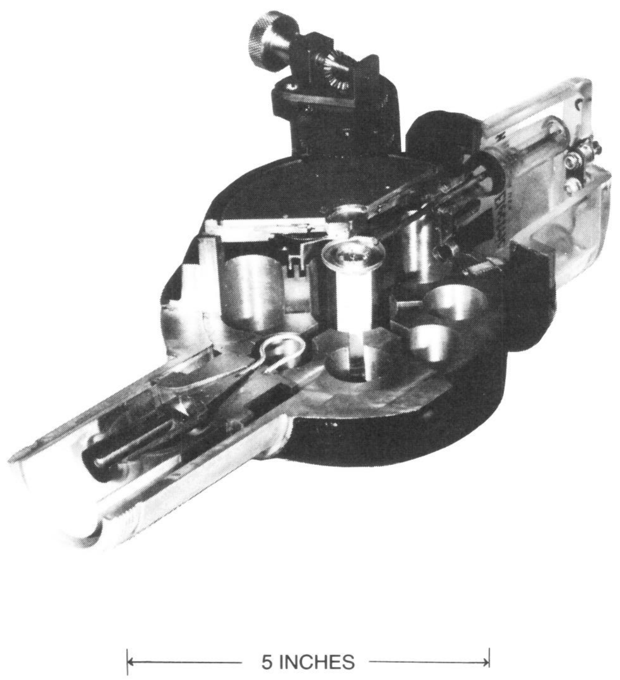


Fig. 3-18. The 4J51 magnetron, which had a vacuum diaphragm to attain smoothly controllable movement inside an envelope of resonator pins, allowing tunable frequency.

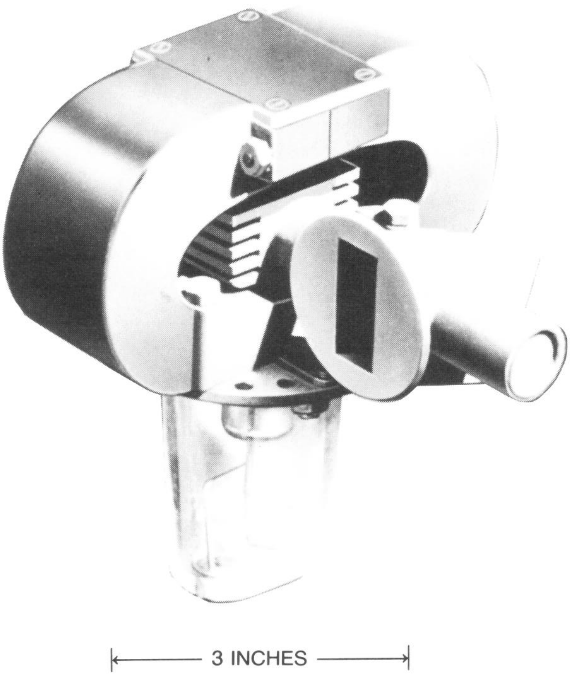


Fig. 3-19. The 2J55 packaged tube magnetron, which featured an external magnet as an integral part of the device. Magnet weight and size were reduced considerably in this design.

A special problem of the magnetron is the cathode, because of the enormous peak currents it must supply in short pulses. Also, it is subjected to intense back bombardment from electrons that gain energy and return to the cathode. Generally, the use of a sprayed oxide cathode is satisfactory in those tubes operating at longer wavelengths, above about 10 cm, where peak emission of 10 to 30 A/cm^2 is required. However, when short wavelengths and high power are to be attained, the small size requires both close anode-cathode spacing and high currents. Arcing becomes a primary problem, and the cathode surface is rapidly destroyed. Studies of these difficulties eventually led to the matrix cathode, in which, at first, finely divided nickel and barium plus strontium carbonates were mixed and applied, held in place by a nickel mesh. The final version consisted of a coarse nickel powder and the carbonates, the mixture being sintered onto the surface of a machined nickel cathode base. Whereas lives of a few tens of hours were experienced in use of simple oxide-coated cathodes in the higher-frequency tubes, the matrix cathode extended the life to a few thousand hours.

Adapting a device as complicated as the magnetron to economical volume manufacture required close cooperative efforts between Bell Laboratories and Western Electric. The magnetron requires massive machine operations to close tolerances in copper. It also requires glass-to-metal seals of highest integrity, reproducible assembly operations, air exhaust, and cathode activation. Western Electric met these challenges. Many of the 75 different codes developed by Bell Laboratories were manufactured in quantity for the armed services. These ranged in frequency from 600 MHz to 30,000 MHz and in power up to 3 megawatts (MW).

The major Bell Laboratories contributions to the war effort may be summarized as follows: (1) scaling of desirable strapping features of the magnetron anode for obtaining adequate mode separation and clean single-frequency oscillation from 3 GHz to 10 GHz; (2) obtaining manufacturable and reproducible output circuits; (3) making the magnetron tunable; (4) developing a rugged cathode; (5) developing packaged tube-magnet structures; (6) achieving completed device designs that could be reproducibly manufactured using reasonable parts tolerances.

In the postwar period, two magnetrons—one X-band at 250 kW and the other S-band at 1000 kW—were produced in large numbers by Western Electric until 1968. (See *National Service in War and Peace (1925-1975)*, p. 372.) The most innovative postwar improvement in magnetron design was the coaxial cavity magnetron conceived by J. Feinstein at Bell Laboratories in 1954.[29,30] It achieved mode separation, high efficiency, stability, and ease of mechanical tuning by surrounding the conventional magnetron anode configuration with a high-Q coaxial cavity. The TE_{011} mode of the cavity was coupled to the anode through slots in the back wall of every other quarter-wave cavity. As a result, the magnetron output frequency could be tuned simply by moving a single plunger in the outer coaxial cavity. The 7208 Ku-band (15.5–17.5 GHz) magnetron was produced by Western Electric in Laureldale, Pennsylvania. [Fig. 3-20] It was employed in aircraft radar, and, 30 years after its invention, a wide variety of modified versions of the coaxial cavity magnetron were still being manufactured by several companies for the military.

3.4 Gas-Filled Tubes for Radar

A formidable problem in radar operation existed in designing a transmit-receive switch (commonly referred to as a TR box). It had to isolate the radar receiver so that it was not damaged or even overloaded by transmitted pulses of high-kilowatt or megawatt peak power; then in nanoseconds to microseconds, it had to switch so that a microwatt radar return signal was applied to a receiver operating at full sensitivity. Without such a device, it would be necessary to provide separate antennas for transmitter and receiver, which would be costly, too large, and too complex. Even then some kind of protection would be required to prevent receiver overload.

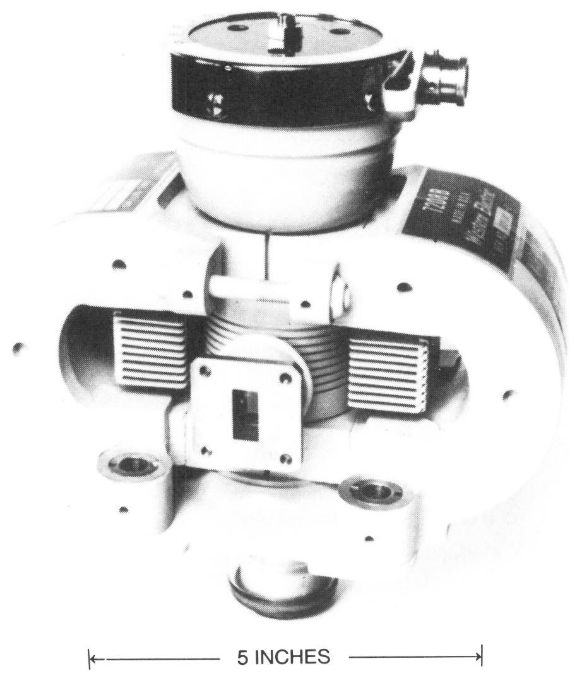


Fig. 3-20. The 7208 coaxial cavity magnetron, employed in military applications for over 30 years. Motion of a single plunger tunes the device.

Two primary functions in a radar transmit-receive array that can be fulfilled by gas tubes are: (1) the switching of stored charge in a pulse-forming network to a transmitting tube such as the magnetron, and (2) the switching of the antenna from transmitter to receiver. Radar advances at Bell Laboratories required rapid progress in the design of tubes for both applications.[31]

Initially, an open-air rotary, motor-driven spark gap was used to pulse the transmitting magnetron from the network. At high voltage, this arrangement operates well. At lower voltages of less than 5 kilovolts, initiation of the discharge is erratic; it was made successful by introducing auxiliary sharp points on each cathode, which started the discharge. However, the device was too bulky for airborne use and became erratic at high altitude. Fixed-gap tubes were then developed, generally using aluminum cathodes and a hydrogen and argon gas fill. A longer-life type used a sintered iron matrix saturated with mercury. The 1B42 is typical of this class, with over 1000 hours of life. Four basic switching tubes in this class were developed.

The earliest radar application was of the 709A vacuum oscillator tube with the addition of internal gas to provide an arc under transmitted power

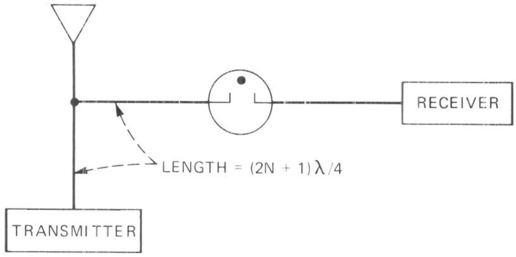


Fig. 3-21. Schematic of the shunt-branching circuit incorporating the 709A tube used as a radar transmit-receive switch, thus allowing the use of a single radar antenna.

level. A tuned cavity around the tube further increases voltage at a given power, protects the tube from high ambient RF fields, and lowers arc extinguish time. The tube was used in a shunt-branching circuit as shown in Fig. 3-21. Three tubes were designed specially for use in a TR box. These were the 721A, 724B, and 1B23, as shown in Fig. 3-22. It was found that the best gas is a combination of water vapor plus hydrogen. The tubes were generally applied in series with the receiver line. For transmitting, the TR tube prevents much power from reaching the receiver; for receiving, the TR position is adjusted so that it is an even number of quarter-wavelengths from the effective short circuit represented by the transmitter, so that maximum voltage is induced across the receiver input. These tubes were made in quantity: in 1944, some 400,000 of the three types for TR use were manufactured.

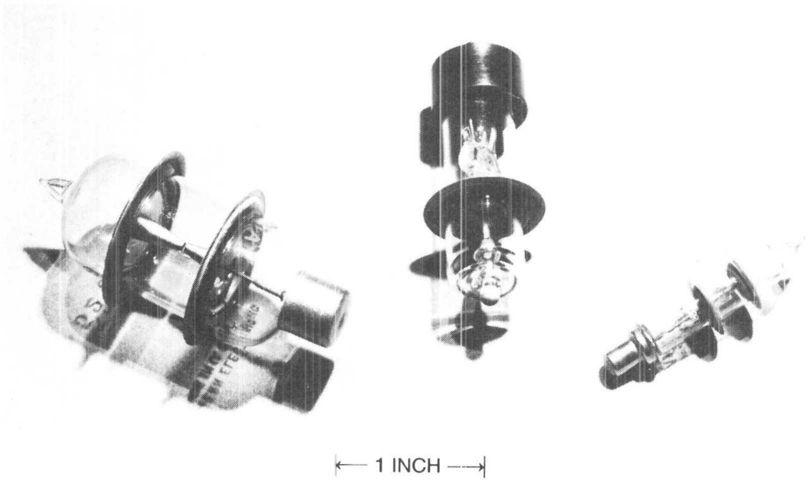


Fig. 3-22. Three tubes designed for transmit-receive use: left to right, 721A, 724B, 1B23.

IV. POST-WORLD WAR II PERIOD

As the demand for telephone service rapidly increased after the close of World War II, the need for outside telephone plant increased as well. Further, it was expected that television would also grow rapidly. The areas of major tube application were radio relay and carrier transmission systems.

Postwar developments can be appreciated only with the perspective of a few earlier events. During the late 1930s, there was heightened activity in the development of new types of transmission systems requiring tubes capable of performing at higher frequencies. The 380-series tubes—primarily designed for low-power applications through audio and ultrahigh frequencies—were useful in both radio and carrier transmission systems. The importance of these tubes in World War II and in the postwar era is covered in section III of this chapter.

The 384A and 386A were used in repeaters of the L1 coaxial system, first made available in 1939 for a field trial between New York City and Philadelphia, Pennsylvania. Commercial service of an L1 system between Stevens Point, Wisconsin and Minneapolis, Minnesota was established in June 1941.[32] The L1 system could provide 480 telephone channels or one television channel on a pair of coaxial cables.

The UHF tubes were used in radio telephony as well as in wire transmission. As early as 1941, a 12-channel, 150-MHz system was in operation across Chesapeake Bay. The successful operation of the multiplex radio link demonstrated that radio telephony had an important place in the new era of communications systems. One of the UHF tubes developed for the Chesapeake Bay crossing was the 363A. The tube is shown in Fig. 3-23. It was a lined-up grid pentode. The plate was solely supported by its lead from the glass envelope, and no insulating material within the tube was subjected to high RF potentials. The tube operated most efficiently between 30 and 85 MHz, but could be operated above 85 MHz by reducing the plate dissipation.

The Chesapeake crossing covered 25 miles from Cape Henry, Virginia to Cape Charles, Maryland. Inserting this radio link in a K carrier system saved about 400 miles of wire carrier.

During World War II, as much nonmilitary work as possible was continued, and in early 1944, a permit was obtained for a repeatered radio relay system between New York City and Boston, Massachusetts. (See *Communications Sciences (1925-1980)*, Chapter 5, section 2.2.) This system, designated TDX, used two-cavity klystrons, coded 402A, as output tubes.[33] The system became operational by late 1947. Two years later, long-haul transmission was improved by introduction of the TD-2 system, using a microwave triode as an output amplifier.[34] Later, the TH and TD-3 systems were developed, using traveling wave tubes as output amplifiers.

The history of carrier systems and the application of electron tubes in them is longer than that of radio systems. The significant contributions

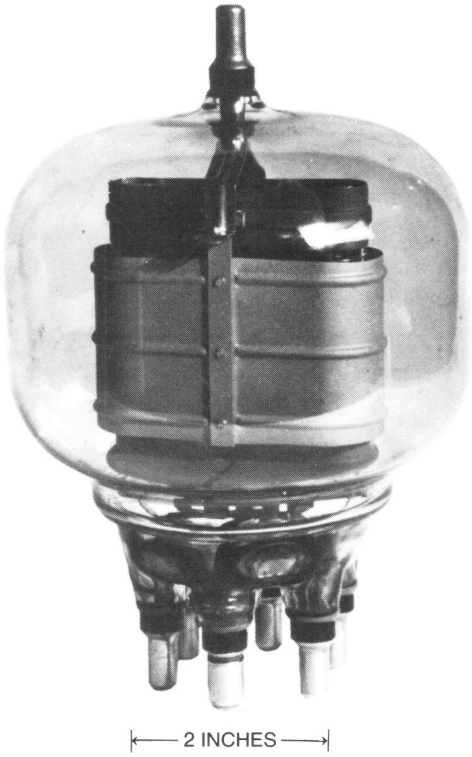


Fig. 3-23. The 363A pentode, used in ultrahigh-frequency radio telephony transmission across the Chesapeake Bay in 1941. It operated most efficiently between 30 and 85 MHz.

following World War II were in the area commonly referred to as frame grid tubes; these were of much higher performance, and led to expanded bandwidth capability. The same devices also found application in radio systems as IF amplifiers of high performance.

Of great importance to the growing body of tube knowledge, although not produced in quantity, were tubes for continued military work and for submarine cable use. All-important to each type of tube is the understanding of cathode operation, which accumulated in depth in the two decades following the end of World War II.

4.1 Cathode Improvement

As noted earlier, estimates of average life of oxide cathodes in repeater-type tubes had been 20,000 hours as early as 1930. Most progress had been made by empirical methods, such as optimizing the processing cycles and obtaining maximum cleanliness, and by conservative operation at low current densities. The result of such progress, typified by the 310A, was

a projected average life of 50 years. Historically, the expected maximum allowable current density for an oxide cathode was 0.5 A/cm^2; even at that level, life tended to be only a few thousand hours. Therefore, typical telephone tubes were run at densities of less than 0.1 A/cm^2. With the advances being made in tubes for radio relay, operation at higher densities or at moderate densities for very long lives became economically important. It was expected that the only way predictable long life could be attained would be by a more complete understanding of the cathode than existed at the close of World War II.

It was long known that chemical reactions occur in the oxide cathode between the supporting metal base and the coating of barium, strontium, and sometimes calcium oxides. The base metal was invariably nickel. This system was found by experiment to yield the highest electron emission per watt of heating power attainable in a readily manufacturable form. However, it was always true that the emission and life depended critically on the composition of the nickel base alloy; tube manufacture required a life test run of each new nickel alloy melt, and acceptance or rejection was based on this test. It was also found quite early that the nickel itself does not react perceptibly with the oxides, and very pure nickel resulted in lower emission than suitable nickel alloys. Thus, the materials in solution in the nickel-base metal alloy were of critical importance. Some elements, like silicon, readily react with the oxides to produce free barium, but result in a compound at the nickel-oxide interface that presents an impedance in series with the cathode. Others, like magnesium, tungsten, and zirconium, readily react without forming a harmful interface layer. Progress in cathode understanding would require understanding of the characteristics of these impurities in the base metal and their control.

Research in the metallurgical department resulted, by the early 1950s, in the ability to produce nickel with no impurity above the trace level (less than 50 parts per million) and, importantly, the ability to reintroduce controlled amounts of desired elements.[35] In the same time period, much had been learned about the diffusion rates of the elements in nickel and their reaction with alkaline earth oxides.[36] With this data, it became possible to predict the most favorable elements to add to nickel cathode bases, the operation temperatures to obtain the optimum element arrival rate, and the length of life of devices. Specifically, the following main conclusions were drawn:

(1) There is an optimum rate of atomic barium (and/or strontium) liberation, by reaction between a reducing element diffusing from the nickel base and the oxides, for a given current density of emission. This rate is 10^{-8} micromole/cm^2/sec for an emission density of 200 mA/cm^2, for example.

(2) At a given temperature, thickness of the nickel base, and concentration of the reducing element, the barium liberation rate can be calculated.

By 1960, the theory had been tested by extended life studies on both laboratory and production tubes, and the modifying effects of internal tube environment were recognized.[37] [Fig. 3-24]

During about the last two decades in which the vacuum tube was the predominant amplifying device, Bell System needs were mostly in two categories: (1) the microwave types—traveling wave tubes, triodes, and klystrons; and (2) grid-controlled carrier or receiving types. The former can possibly use cathodes in a wide range of nickel thicknesses, although the required current density is high in order to obtain good electron-circuit coupling and usable gain with reasonable tube size. The latter are limited to thin nickel cathodes because of requirements for low heater power and the need for a large area of electron emission. In this category, the density of emission requirements was initially moderate, but increased with progress in design.

Laboratory life studies indicated zirconium to be the preferred additive element for use in tubes with cathodes about 0.05 inch thick. The time to depletion of half the zirconium, for 0.1 percent by weight concentration, was predicted to be 20 years at 200 mA/cm^2 density and normal operating temperatures. However, with 0.003-inch-thick cathodes, the equivalent time is only about 2000 hours. Study of materials for this case resulted in the finding that a combination of tungsten and magnesium would give comparable predicted lifetimes.

Application of the new knowledge to production tubes rather than to laboratory tubes resulted in some surprises. Even though thick nickel could usually be used in microwave tubes, these devices required much internal glass and metal area as compared with the cathode area. In the carrier-

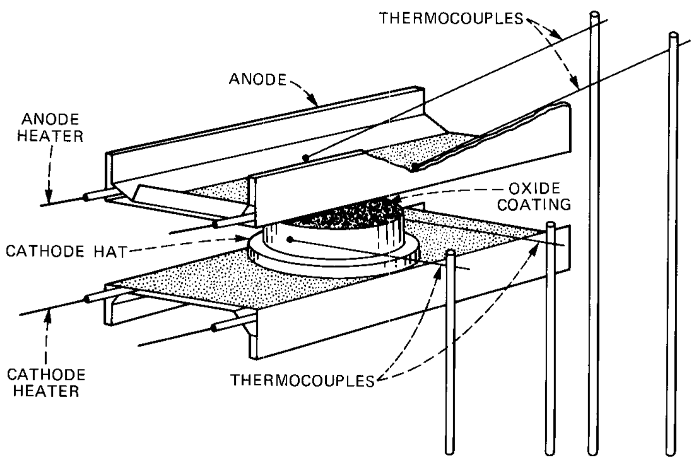


Fig. 3-24. Diagram of a planar diode used in studies aimed at extending the life of cathodes.

type tubes, however, the cathode area is a much larger proportion of the total internal area. It was found that the former cathodes, operating at high current density, were much more easily disrupted by processing variations than were the carrier types. As a result, the pure nickel, single-additive technology was not generally adapted to microwave tubes, whereas the technology was successful in grid-controlled carrier types. Essentially all grid-controlled tubes made by Western Electric used the tungsten-magnesium alloy. The microwave tubes used an alloy containing several reducing elements.

In 1964, another contribution was made to the oxide cathode art, the coated powder cathode.[38] It was shown that under high-current emission, the current flow may cause a high field across the coating. This field will cause positive ion donors to be attracted toward the base metal, leaving a depletion at the cathode coating surface. If the gradient across the coating could be reduced, the surface depletion would also be less under high-current-density operation. To this end, the particles of carbonate that make up the coating were individually coated by a thin nickel layer. The carbonate was later converted to oxide during activation of the cathode, but the nickel coating remained. Experience proved that excellent life was obtained at a current density as high as 1 A/cm^2. The coated powder cathode was used in traveling wave tubes and PICTUREPHONE visual telephone service. An additional benefit from use of the cathode was its lessened sensitivity to process variables.

4.2 Klystrons and Microwave Triodes

Of the common carrier bands available for radio relay purposes, the one centered at 4 GHz was preferable from the point of view of directivity, antenna size, and rain attenuation. At the end of World War II, prior to the development of the traveling wave tube, only velocity variation tubes (klystrons) and close-spaced gridded planar tubes were available as satisfactory RF amplifiers at 4 GHz. At the time, the only proven reliable vacuum seals were metal to glass, the ceramic-to-metal vacuum seal technology having just been born. These considerations limited the design of multicavity klystrons to two cavities (rather than three- or four-cavity designs) and high beam voltages (1500 V), since low voltages require close spacings. To provide the gain, power output, and bandwidth required of a 4-GHz RF amplifier, four stages dissipating 180 W were needed.

If one could shrink the interelement spacings of the then current microwave triodes to less than 0.001 inch, it appeared that a simpler, low-voltage and lower-cost RF amplifier could be produced. Consequently, a close-spaced planar triode design, later coded the 416A, was begun by J. A. Morton and his associates with an objective of 0.0005-inch grid spacing, and a grid pitch of 1000 turns per inch using 0.0003-inch diameter wire.[39]

A drawing of the resultant structure is shown in Fig. 3-25. Nonconventional cathode construction was required to provide for the close spacing. The cathode was coated on a thick nickel base assembled on a ceramic reference ring. These elements were made coplanar by a grinding operation after assembly. A special technique was developed to coat the cathode with a precise application of high-density carbonate coating. The applied thickness was limited to 0.0005 inch, and the assembly was supported by spring loading the ceramic cathode reference ring to the grid frame with a precision spacer. The thickness of the spacer is the sum of the cathode coating thickness, the change in cathode position when heated to operating temperature, and the desired cathode-to-grid spacing.

The grid consisted of parallel wires wound on a molybdenum grid frame. Experience showed that the tungsten grid wire could be drawn to 0.0005 inch. The diameter was further reduced to 0.0003 inch by electrochemical etching in a continuous etcher that was feedback controlled from a resistivity measurement made on the completed wire. The grid frames were given an evaporated gold plating on one side and then mounted back to back in a winding machine chuck. The winding pitch was obtained by reducing the feed obtained from a precision lead screw by a factor of 10 using a sine bar lever. Winding tension was controlled by a dynamic system that overcame the "whip" caused by rotating the flat grid frame.

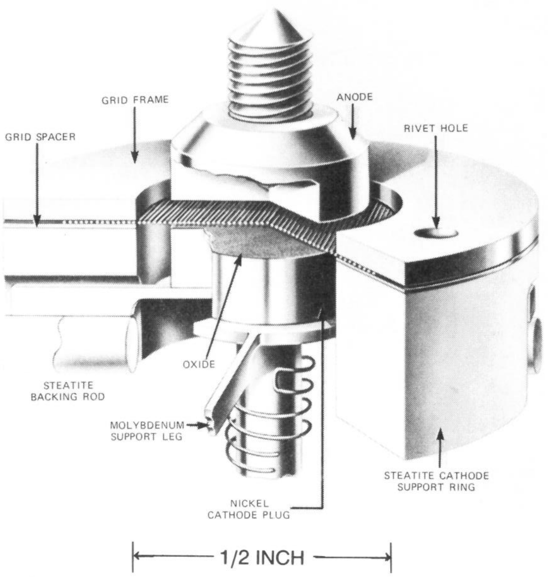


Fig. 3-25. Close-spaced microwave triode, developed by a group led by J. A. Morton. The design objective was an improved, low-voltage, cost-effective RF amplifier for 4-GHz operation.

At an operating potential of 200 V and a current density of 0.2 A/cm^2, three of these tubes cascaded in an appropriate circuit produced 23-dB gain, 0.5 W of power output with greater than 30-MHz bandwidth. The extent to which dimensions were reduced can be appreciated from Fig. 3-26, which compares the 416A with a more conventional triode of that time.

With continued development work, the average life of triodes operating in low-level input stages eventually reached 40,000 hours; a life of 15,000 hours was typical at 0.5-W output. Further development allowed operation of the amplifier at 1-W output.

Tube development and production started by using nickel-iron-cobalt glass seals. As the metal-to-ceramic seal technology evolved, the glass-to-metal seals eventually were replaced by beryllia ceramic-to-metal seals. This resulted in reduced RF losses in the seals and increased RF power output.[34] The high thermal conduction of the beryllia seals allowed the total dc power input to be increased. With these changes, the power output of the 4-GHz amplifier eventually reached 5 W.

The 416 series of close-spaced triodes was used as transmitter amplifiers in the TD-2 and TD-3D radio systems, which started with 0.5-W output and, with a series of improvements, reached ever-increasing power levels until a level of 5 W was achieved. Starting with a route capacity of 2400 telephone message circuits in 1950, a later version of the 4-GHz system was capable of 19,800 circuits per route. In addition, these systems were used for network television and data transmission.[34] At one time, about

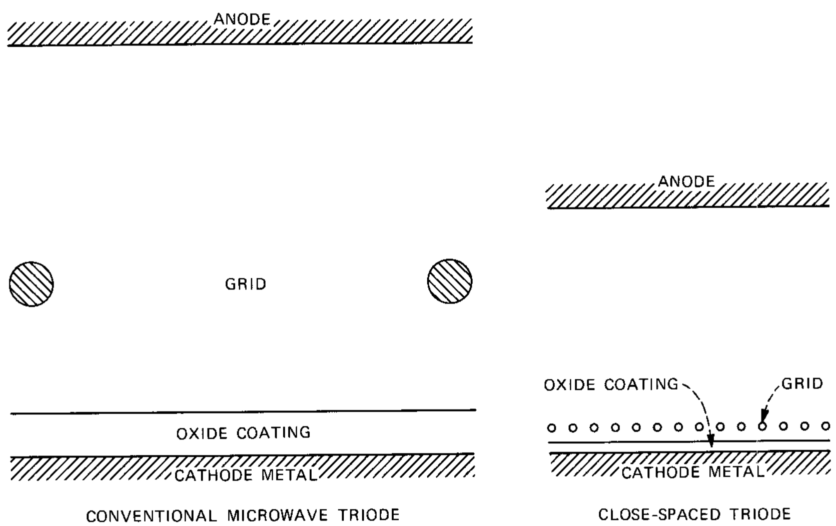


Fig. 3-26. Comparison of sizes and spacings of a 1940s triode (left) and the 416A microwave close-spaced design (right) with a grid spacing of 1/1000 inch.

70 percent of the long-distance circuit miles used radio systems with close-spaced triode amplifiers. About 100,000 tubes were used in amplifier circuits, and more than half that number were used in signal generators and frequency converters.*

4.3 Traveling Wave Tubes

A giant step in microwave-frequency gain-band figure of merit occurred with the invention by R. Kompfner, and the subsequent exploitation by Pierce, of the basic traveling wave interaction scheme.[40] Here was a new amplifier device that presented the promise of large bandwidth and high gain simultaneously. The reason for such capability is implied in the name. Modulation of an electron stream by information to be amplified occurs continuously during nearly synchronous electron beam and electromagnetic (EM) wave travel. There are no frequency limitations caused by transit time. The associated physical structure, together with traveling wave interaction, permits the input, amplification, and output of a wide range of frequencies. There is, however, a limitation on gain set both by requirements for stability and by practical limits on the amount of energy that can be transferred from the electron beam to the EM wave without losing the near synchronism between the motion of the electrons and the wave. (See *Communications Sciences (1925-1980)*, Chapter 4, section III.)

Like other microwave tubes, the traveling wave tube (TWT) operates on the principle of electrons giving up energy to an EM field. The interaction occurs between a linear electron beam and an EM wave that propagates along a slow-wave circuit. This circuit causes the EM wave to follow a route that results in its forward progress in the beam direction being slowed until the latter is the order of 0.1 c (the free space velocity of light). The slow-wave circuit typically surrounds the electron beam. Gain is obtained by adjusting the electron beam velocity to be just slightly faster than the velocity of the EM wave in the direction of the beam axis. The beam is then modulated and, on the average, slowed by its interaction with the EM wave; the kinetic energy lost by the electrons is transferred to the EM wave as the latter progresses toward the output circuit.

Many slow-wave circuits have been devised, but by far the most widely used is a simple wire helix. An EM wave traveling along the wire has a velocity along the helix axis of about $pc/\pi d$, where p is the helix turn-to-turn spacing, d its mean diameter, and c is, again, the free space velocity of light. Typically, the helix is wound to make the axial wave velocity

* Between 1979 and 1983, solid-state amplifiers using gallium arsenide field-effect transistors were installed in place of the electron tube transmitting amplifier. With the replacement of the close-spaced triode, the entire TD radio system was converted to solid-state devices exclusively.

equivalent to that of electrons accelerated through 1000 to 4000 V. Other slow-wave mechanical configurations are useful for higher powers; examples are a series of resonant cavities or a meandering waveguide. Shown in Fig. 3-27 is a schematic of a helix-type tube.

Early important contributions in the TWT field by Bell Laboratories were amplifier stability and quantification of tube design. Later contributions included noise reduction and beam focus. Bell Laboratories also offered the first mechanical design of precision slow wave structures, introduced the first mass-produced TWT, and built rugged TWTs for military and earth satellite use.

By the mid-1950s, several TWT developments were maturing for application. One of these was a 3-GHz low-noise tube, the 6784, for military use. A second, the 444A, a broadband output amplifier, was developed for use in the TH-1 long-haul radio system then being readied for service.[41] In addition to the basic contributions given earlier, the extended research and development program on these two tubes yielded most of the knowledge on TWTs that was applied to succeeding codes. Some of the most significant findings and developments are outlined below.

Ion Damage to Cathodes. Because the TWT is long, there is enhanced probability of positive ion formation from electron-gas molecule collisions even in the most optimally processed tube. The negative space charge of the electron beam tends to prevent the ions from leaving the region of the electron beam. Consequently, many of the ions produced in the region of the slow-wave circuit drift close to the beam axis toward the electron gun and then are accelerated toward the cathode once they enter the anode-cathode space, which provides an accelerating field. It was found that cathode life can be reduced by an order of magnitude from this bombardment. The solution is to design the tube in a way that requires the anode of the electron gun to be biased more positively than the slow wave circuit to effect a barrier to ion travel from the region of the slow wave circuit to the cathode. In all but those tubes designed for the very lowest noise, this practice has been followed.

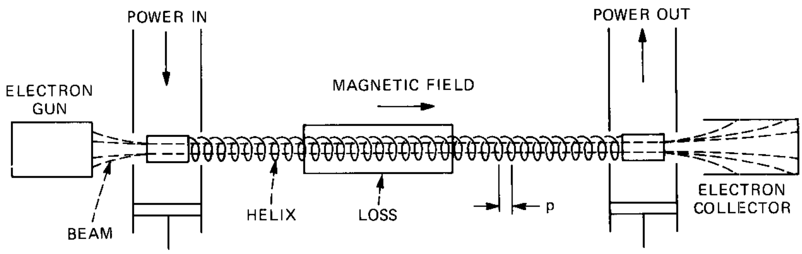


Fig. 3-27. Schematic of a helix-type traveling wave tube. Typically, the helix is wound to make the axial velocity of an RF wave along the helix equivalent to the velocity of electrons.

Collector Depression. By proper mechanical design, it is possible to operate the electron collector under RF drive as low as half the voltage of the slow-wave circuit; by this means overall TWT efficiency is significantly increased because, except for power to heat the electron-emitting cathode, most dissipation in a TWT occurs in the collector electrode.

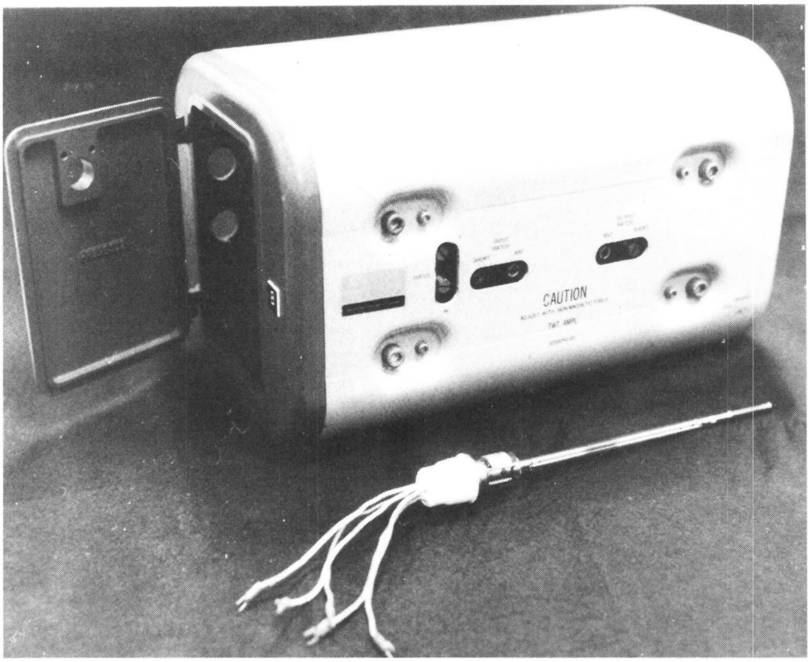
Noise. In tubes designed to deliver moderate power, a converging electron beam is often used to avoid excessive current density from the cathode. The cathode has many times the area of the electron beam focused through the slow-wave structure. This beam compression tends to magnify the growing noise wave that is produced during beam flow. It was found that this wave can be greatly suppressed by introducing controlled magnetic flux at the cathode plane. Noise can often be reduced by an order of magnitude.

Helix Accuracy. There are adverse effects—instability, granularity of gain versus frequency, and intermodulations—that may be produced by periodic variations of pitch in the helical slow-wave circuit. Very accurate winding and means for maintaining accuracy are necessary. The first need was met by machine development, and the second by development of a technique of attaching helix wire to ceramic supporting members at each crossing of the wire. The result, widely used in later tubes, is sufficiently accurate that no evidence of periodicity can be detected.

Magnetic Focusing. Initially, dc solenoids were used for TWT focus. Investigation of materials and physical shapes resulted in a design procedure for attaining minimum material, permanent-magnet focus arrangements using a uniform straight field. For the 444A for the TH-1 radio system, such a circuit was adopted for production. Later in the 1950s, Bell Laboratories contributed to the development of a new scheme for focus, in which a series of ring magnets produces a sinusoidally varying magnetic field.[42,43] Because much less magnetic material is needed than for a uniform field, and because the periodic field produces much lower external leakage magnetic flux, most modern TWT amplifiers use magnetic focusing.

The 444A became the first TWT to be manufactured in significant quantities. Again, by cooperation between Bell Laboratories and Western Electric, assembly techniques peculiar to the TWT were successfully adopted in manufacture, and over 20,000 tubes had been shipped for customer use by the end of 1974. The device was used as the output amplifier and as a source of local oscillator power in TH-1 radio. It consistently delivered more than 7 W of power for periods of 3 to 5 years.

Figure 3-28 shows the 444A tube and focus circuit. The collector was cooled by air flow from centrally located blowers in the TH-1 station. The outer shell, much larger than the actual magnet, was provided to lower leakage fields that might affect nearby apparatus. Succeeding power TWT amplifiers were designed for TD-3 radio, TM radio, and TH-3 radio. All used periodic focus and incorporated the growing body of cathode knowl-



|← 5 INCHES →|

Fig. 3-28. The 444A tube and focus circuit. The outer shell, much larger than the actual magnet, was provided to lower leakage fields that might affect nearby apparatus.

edge to attain long life. One of these, the 461A shown in Fig. 3-29, consistently delivered an average operating life of eight years.

One additional TWT departed somewhat from the general designs, although it borrowed heavily from the technology and processing of them. This is the M4041 tube for the Telstar satellite.[44] To provide 3.5 W of power at 4.0 GHz in an extremely reliable package, this unit had a cathode current density of 80 mA/cm^2, compared to 200 mA/cm^2 in the power tubes. A cathode consisting of ultrapure nickel with zirconium additive, as discussed in section 4.1, was used. This satellite tube was constructed in the laboratory under ultraclean conditions. The focusing circuit was another innovation—a compromise between a heavy straight field system and a periodic system. It used a field reversal at the center. With this circuit, a favorable compromise was reached between total weight and efficiency; weight was cut by a factor of six from a single straight field magnet. Compared with use of a periodic field, a smoother beam profile was maintained, allowing lower collector voltage and therefore higher efficiency, as previously explained. Reliable performance in space was achieved by very careful processing and testing, and selection of tubes

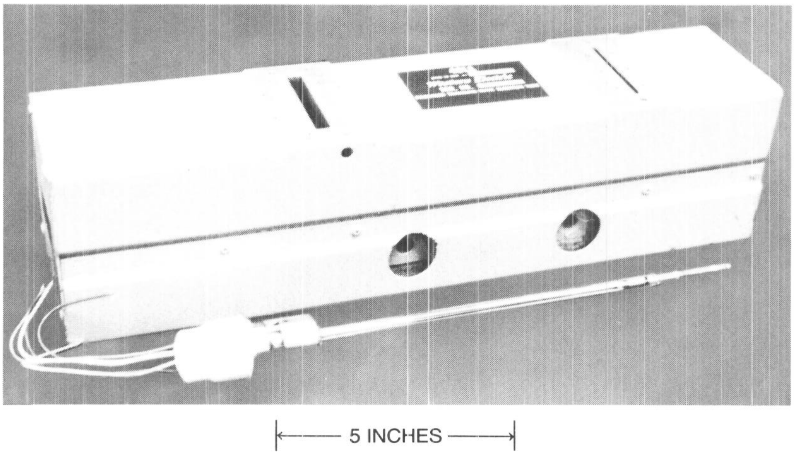


Fig. 3-29. The 461A traveling wave tube consistently delivered an average operating life of eight years.

only after 2000 hours of aging and inspection. The mechanical design was made very rugged to withstand the rocket launch.

Project Telstar also required the largest and most powerful continuous wave (CW) communications TWT developed at Bell Laboratories, the M4040.[45] This tube, a schematic of which is shown in Fig. 3-30, developed under extreme time constraints by R. J. Collier, G. D. Helm, J. P. Laico, and K. M. Striny, was a 2-kW CW traveling wave amplifier, 4 feet long

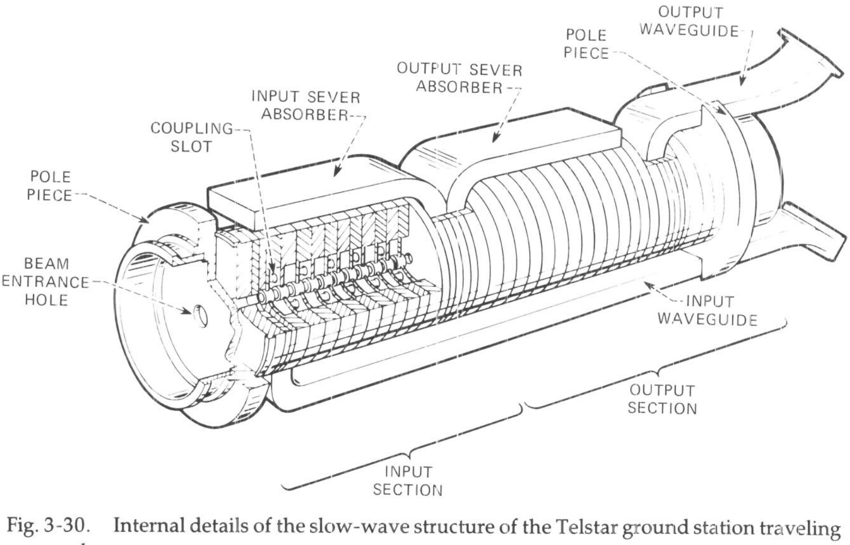


Fig. 3-30. Internal details of the slow-wave structure of the Telstar ground station traveling wave tube.

and weighing 230 pounds. The only nonhelix Bell Laboratories TWT, it employed a coupled-cavity slow-wave structure with a 13-percent bandwidth centered at 6.15 GHz and a gain exceeding 27 dB. In early 1962, M4040s were installed high on the antenna feeds in Telstar ground transmitter stations at Andover, Maine and Pleumeur-Bodou, France; they functioned reliably as the final power amplifier of the signal beamed to the Telstar satellite.

One of the last TWT designs by Bell Laboratories was for the AR6A single-sideband microwave radio system. The performance objectives for this tube, coded 473A, were significantly different from those of its predecessors. Instead of being designed primarily for good efficiency at continuous operation levels near saturation, the 473A had to deliver high, short-period, peak-power output. However, its major requirements were specified at a power output level far below saturation; although it had a peak capability of about 70 W, the critical parameters were measured in the region of 0.5-W output, as shown in Table 3-1.

Many TWTs were investigated for the AR6A application and found lacking in required intermodulation performance. The intermodulation levels for the 473A tube were at least 3 dB lower than any other available tube. The flatness of the third-order intermodulation as a function of power output was superior in the 473A when compared to the other tubes under investigation. Further, the restricted gain-noise sum limit required departure from the conservative electron gun designs previously used. Major features of the 473A met all the above detailed requirements. After a short period of manufacture, it was found that 473A yields were rapidly increasing and shortly exceeded predicted values. Application in AR6A bays demonstrated that the design met all requirements. It was operated with a power supply designed for it and the combination of the tube and the power supply was stable with extended field use. (A total of 293 devices were shipped for field use before Western Electric terminated all TWT manufacture in December 1981.)

No Bell System application of the TWT has taken advantage of the potential instantaneous bandwidth of the device. This is because of statutory frequency assignments and also because modulation systems naturally divide available frequency space into channels. As a result, it has not been necessary to provide wideband input and output circuits.

Table 3-1. Critical Parameters of the 473A TWT

RF gain:	40 to 46 dB
Gain plus noise figure:	69.5 dB max.
Third-order intermodulation:	-90.5 ± 0.4 dB ($P_0 = 19$ to 29 dBm)
Fifth-order intermodulation:	-180 dB ($P_0 = 22$ dBm)
	-160 dB ($P_0 = 18$ dBm)

Mention should be made of a number of experimental electron tubes—both klystrons and TWTs—that were developed for use as oscillators and amplifiers in a millimeter-wave communication system (later referred to as the WT-4 system). Based on the use of the low-loss TE_{01} mode in a circular waveguide, this system was the subject of continuing research at Bell Laboratories and elsewhere from the late 1940s into the 1960s because of its extremely wide transmission band.

A description of such innovative devices as spatial harmonic amplifiers, the backward-wave oscillator, double-stream amplifiers, and other devices using electron-wave interactions is to be found in *Communications Sciences (1925-1980),* Chapter 4.

4.4 High-Figure-of-Merit Carrier Tubes

The need for circuits with greater bandwidth led to continuous evolution in the design and production of low-power, carrier-type grid control tubes. The most significant steps were in the application of known design principles to maximize the gain-bandwidth (GB) product figure of merit and application of new cathode technology, as previously described.

Investigation of the requirements for high-GB product revealed that it is largely a function of transconductance: GB $\sim g_m/(C_1 + C_2)$, where C_1 and C_2 are tube input and output capacitances. Since by definition, g_m is the change in plate current divided by the corresponding change in grid-to-cathode voltage controlling the plate current, anything that will increase the influence of the grid voltage (signal input) on plate current flow is desirable. Moving the control grid closer to the cathode will do this. Unfortunately, it will also increase C_1; however, the improvement in g_m much more than offsets this increase, particularly if a small grid wire is used. For a tetrode or pentode tube, a decrease in cathode-to-grid spacing requires that the screen grid also be moved closer to the cathode if the operating voltage is not to be unusually high. Similarly, the plate should be moved closer, both to operate at moderate voltage and to prevent influence on the electrical characteristics due to space charge.

The 6AK5/403A represented the state of the art at the end of World War II. The improvements in subsequent designs are shown in Table 3-2. These improvements were achieved by changes in mechanical design, precision piece parts, newer cathode technology, and statistical controls.

Table 3-2. Improvements in the 6AK5 Series

Tube	6AK5/408A	404A	435A	436A
Figure of merit (gain-bandwidth product, MHz)	72	123	146	165

Bell Laboratories contributions along these lines can be described by citing development of tubes for use in the L3 coaxial system.[46]

The 0.0035-inch cathode grid spacing of the 6AK5 is about the minimum for conventional construction techniques. Studies of designs for possible L3 amplifier tubes indicated that the cathode grid spacing should be 0.0025 inch. The smaller grid cathode spacing required a new grid design, as shown in Fig. 3-31. The grid frame consisted of two side rods supported

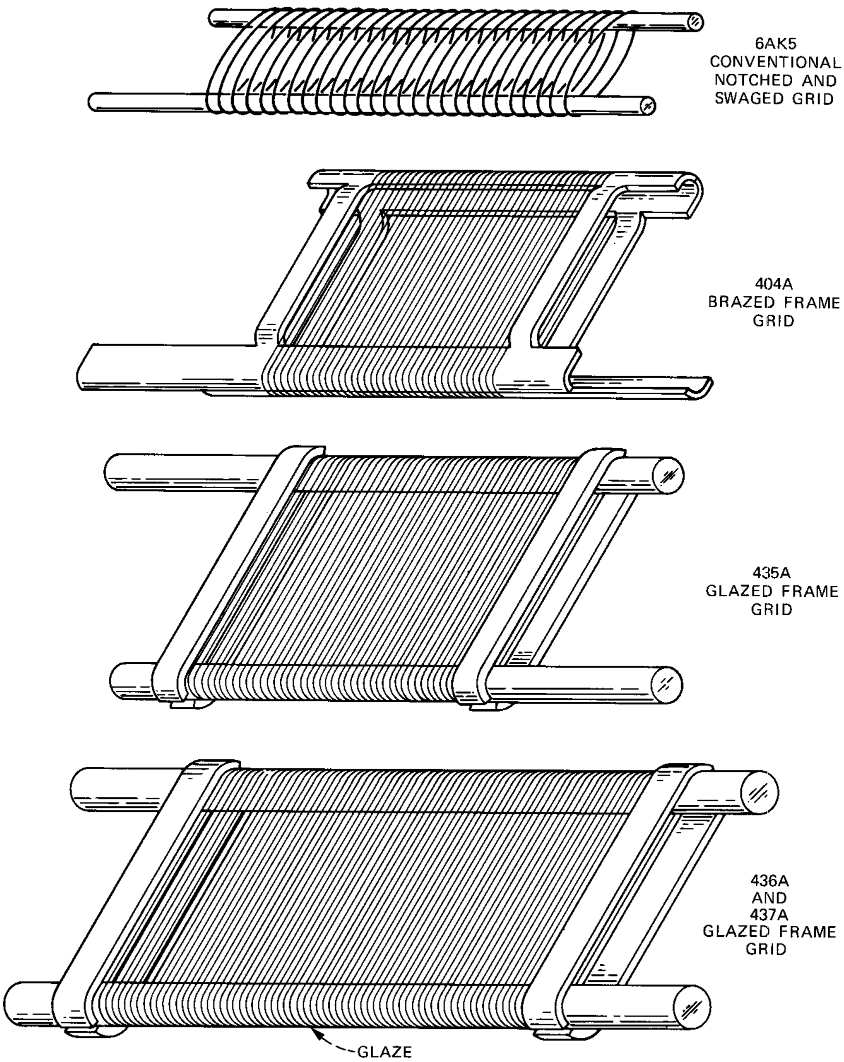


Fig. 3-31. The 0.0035-inch cathode grid spacing of the 6AK5 is about the minimum for conventional grid construction techniques (top). New grid designs were required for closer spacing; three examples are shown.

by straps at each end, leaving a space to be occupied by the grid laterals. The side rods were ground to precise dimensions to control the grid cathode spacing. The grid was wound on the frame and held under tension, and a glass frit glaze was fired on to maintain the tension. New machines were developed to obtain the precision required in winding these grids. Gold plating, important to inhibit thermionic emission from the grid, which was heated by the nearby cathode, was put on the grid to a thickness of 20 microinches. The 0.0003-inch diameter tungsten wire was wound at 410 turns per inch on the 436A and 380 turns per inch on the 435A. The tension in the lateral wire was equal to 200,000 pounds per square inch, an order of magnitude greater than the working stress of architectural steel. The screen grid was wound by conventional means, and the tube elements mounted on mica supports. The mica dimensions had tolerances tighter than any previous designs. The technique used was to refurbish dies as wear approached specified limits. Multiple sets of dies were made so that a usable die to specified tolerances was available at all times. Figure 3-32 is a cutaway view of the 436A, an L3 tetrode tube. Extensive testing

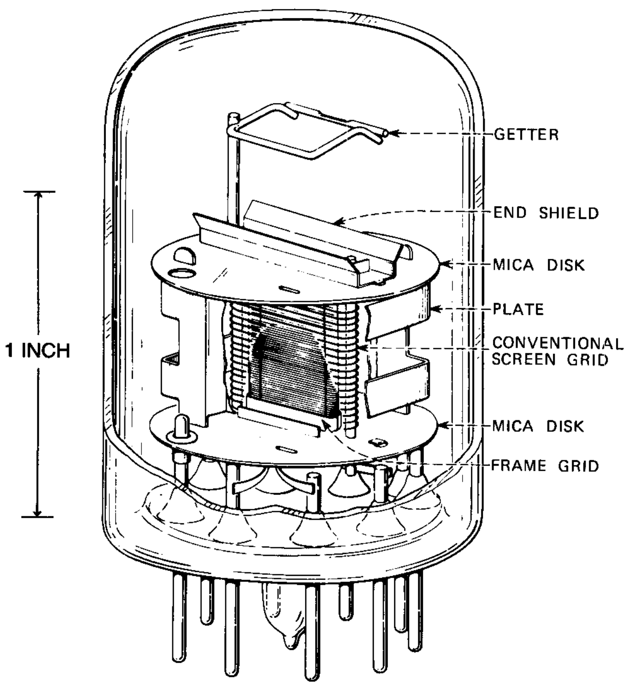


Fig. 3-32. The 436A tetrode tube for the L3 coaxial cable transmission system. Grid wire was 0.0003 inch in diameter, wound 410 turns per inch.

proved the soundness of these construction methods, and the tube was manufactured at high yield. The L3 coaxial system employed careful statistical control methods to assure that minor manufacturing deviations did not pile up to cause out-of-specification system performance.[47]

4.5 Gas Tubes

From the 1930s through the 1950s (except for the World War II years), over 20 types of cold-cathode tubes were designed and produced for the Bell System, resulting in a design experience of providing unique structures and unique improvements in the normal characteristics of industrial-type applications. Some of the developments were as follows.

(1) An unusually stable voltage reference tube, the 423C, for the TD-2 radio relay automatic switching system and for the TH and TJ systems. [Fig. 3-33] This tube used parallel, flat, pure molybdenum electrodes that would provide an operating voltage stable to less than 0.1 V (typically 0.02 V) out of 100 V per 1000 hours of operation, an otherwise unavailable

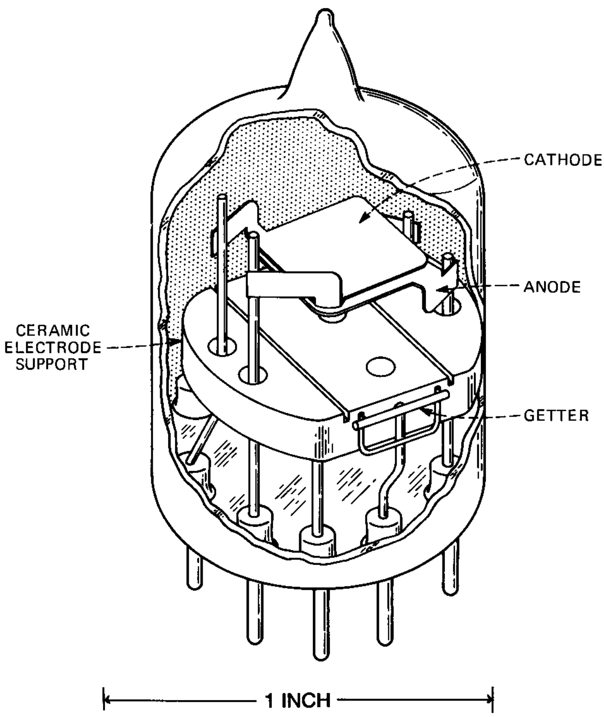


Fig. 3-33. The 423C cold cathode gas tube, used to provide a reference voltage for the TD-2, TH, and TJ microwave radio transmission systems. [Gewartowski and Watson, *Principles of Electron Tubes* (1956): 556.]

degree of stability. A later version, the 432B, provided the oscillation-free and surge-free reference voltage required by the A2A and A2B video transmission systems.

(2) A voltage regulator tube, the 427A, providing nominally 0.1-percent regulation from 5 to 40 mA, in contrast to the 5-percent regulation of commercial tubes. This tube also used parallel molybdenum electrodes to obtain needed stability.

(3) A counting or stepping tube, the 6167 and 439A, in the early 1950s,[48,49] which would transfer the glow discharge from cathode to cathode in response to incoming pulses by the action of the glow discharge moving from the location (on each cathode) of initial discharge to a preferred location in the direction of the stepping or counting movement. The arrangement of the electrodes is shown in Fig. 3-34 and again schematically in Fig. 3-35. The cathode design used the recently developed concept of a hollow region of a cathode being the preferred discharge location. In this case, the hollow was formed by coiling molybdenum wire, the wire also providing a mounting leg and the "pick-up" extension for the discharge. While counting tubes with simpler electrode structures later became available commercially, this tube provided manufacturing experience with the hollow cathode for later use.

Fig. 3-34. Arrangement of electrodes of the 6167 stepping (counting) tube.

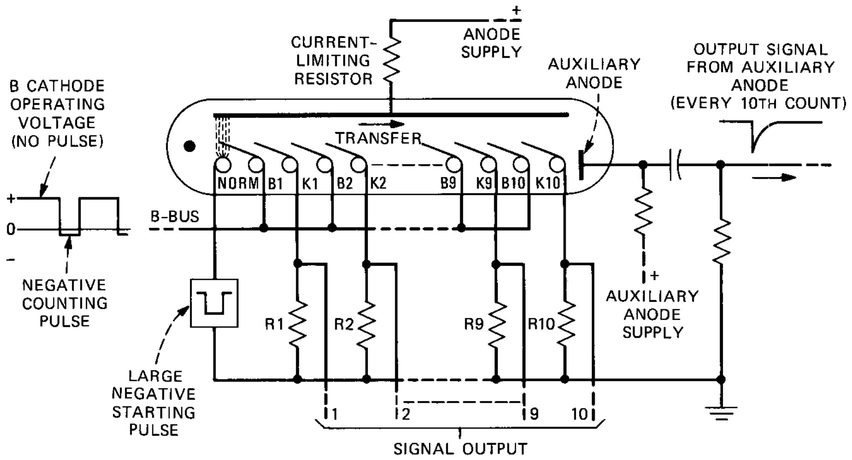


Fig. 3-35. Schematic of the 6167 counting action. Glow discharge stepped from position to position in response to input pulses.

V. ELECTRON TUBES FOR SUBMARINE CABLE SYSTEMS

The electron tubes developed for submarine telephone cable systems were probably the most reliable tubes ever made. Because of the use of electron tubes in costly to access sea-bottom repeaters, the first transatlantic cable system, TAT-1, was recognized as a very ambitious project. As former Bell Laboratories president W. O. Baker stated in the *Bell Labs News* of January 29, 1979, "TAT-1, for its time, ranked in engineering difficulty with the later feat of putting an earth satellite into orbit."[50]

While all components of the system were required to be highly reliable, the tubes, with a known wear-out mechanism, were the key to the success of the project. Reliability was designed and built into the tubes. At Bell Laboratories, work on tubes for use in a proposed transatlantic system was started in 1933.[51] A short field trial cable from Key West, Florida to Havana, Cuba was laid in 1950, and the first major system was put into commercial operation across the Atlantic in 1956.

The suggested objective for submerged repeaters was that the tubes should not be responsible for a system failure for many (possibly 20) years. At that time, an average operating life of a few thousand hours (perhaps three to four months) was satisfactory for tubes in the home entertainment field. In land-based telephone equipment, an average life of a few years was considered reasonable. To meet the 20-year objective, no new or untried technologies were introduced; the emphasis was on conservative design and careful manufacture.

In design, three basic assumptions were made: (1) operation at the lowest practical cathode temperature would result in the longest thermionic

life, (2) operating anode and screen grid voltages for the tubes should be kept low, and (3) the cathode current density should be kept as low as practicable.

In manufacture, care would be exercised in the selection and processing of materials, in fabrication procedures, and in detailed testing; long-term aging of all tubes would be carried out. Records of these items would be reviewed as part of the final selection of individual tubes for use in the repeaters. This selection concept was unique at that time.

The tube developed and manufactured by Bell Laboratories was the 175HQ shown in Fig. 3-36. The operating characteristics were cathode temperature, 670 degrees C (true); anode and screen voltages, 32 to 51 V; and cathode current density 0.7 mA/cm^2.

The cathode operating temperature was derived empirically. Life tests were run for many years, even during World War II when testing had to be squeezed in, and while the bulk of the work was done at about 710 degrees C, the results at 670 degrees C and 615 degrees C indicated that 670 degrees C would be appropriate. Normal cathode temperatures were approximately 750 degrees C.

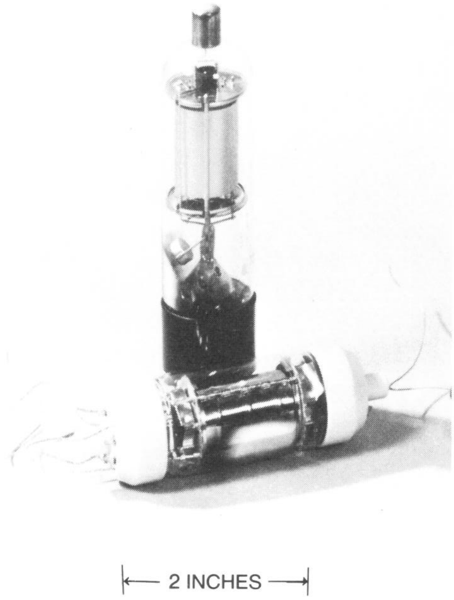


Fig. 3-36. Early model of the 175HQ (upright) and the final version (on side). In the first transatlantic system, 306 of these tubes operated for 22 years without failure.

Life tests were also used to study the effects of anode and screen grid voltages over the range of 40 to 60 V. No essential differences in performance were noted after eight years of operation, so the voltages listed above reflected the needs of the system. Voltages used in other vacuum tube amplifiers were typically 150 to 200 V.

The effect of cathode current density on thermionic life was also studied by life tests. After about 14 years, there was practically no difference over a 12-to-1 range of densities, i.e., 2.5 mA/cm^2 and 0.2 mA/cm^2. The final choice was to operate at 0.7 mA/cm^2, in contrast to normal current density of 50 mA/cm^2.

One common cause of tube deterioration with life is the formation of an interface layer on the surface of the cathode sleeve. As mentioned above, this depends in a complex way on the chemical composition of the cathode core material and, in effect, introduces a resistance in series with the cathode. This results in negative feedback and reduces the effective transconductance of the tube. The low transconductance of the 175HQ tube (1000 mS), the low cathode temperature, and the large cathode area were favorable factors to minimize the effects of this interface resistance. Again, as a result of life testing, one batch of nickel (melt 84) was selected for use in the production.

The tungsten heater for maintaining the cathode at the proper temperature was critical, since the heaters of all tubes in the system were connected in series. One open heater would disrupt the cable. Protection of the heaters from power surges was provided by a bypass gas tube across the three heaters of each repeater. Careful selection and control of the tungsten wire was instituted. The heaters were run at 1100 degrees C, which is well below that used in conventional tubes.

All 175HQ tubes used in submarine cables were made at Bell Laboratories, under the close supervision of many of the original development engineers. Fabrication was carried out with extreme care by operators specially selected for the job. Nylon smocks, acetate rubber gloves, and restricted areas were early steps toward modern ultraclean facilities. Thorough mechanical and electrical inspections over a 5000-hour aging period provided information for selection of individual tubes for cable use. By normal commercial test limits, the yield would have been about 98 percent. With the criteria used, only one tube in seven was accepted.

The original objective of a 20-year life was met by the first transatlantic cable, where 306 tubes operated for 22 years without a tube-related failure. This cable was retired in November 1978, for economic reasons. At that time, the 1608 175HQ tubes on sea bottom in seven cable systems had given 287 million tube-hours of trouble-free service.

The development of a new tube for the SD (1-MHz) cable system was started in 1955. The resulting 455A-F tubes[52] were designed by Bell Laboratories and manufactured by Western Electric in Allentown, Pennsylvania

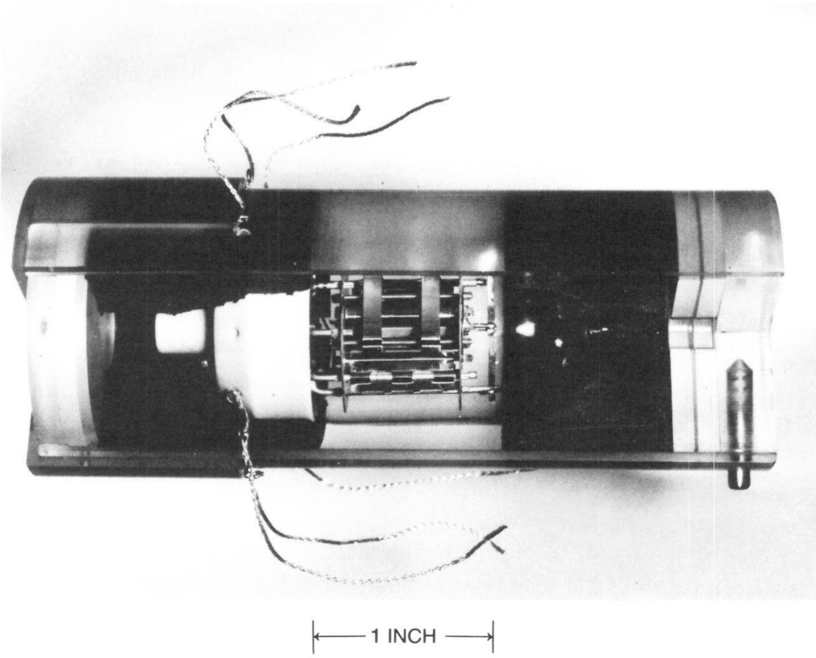


Fig. 3-37. The 455A tube cushioned in a methacrylate housing, used in the 1-MHz SD submarine cable system. As of November 1978, 5874 such tubes in 10 cable systems had accumulated 738 million tube-hours of service.

with the close surveillance and cooperation of a resident group of Bell Laboratories engineering personnel. This tube is shown in Fig. 3-37.

To meet the same 20-year system reliability objective, developers of the new tube used an extension of the 175HQ design philosophy, updated in those areas where significant progress in basic knowledge had been made. For the broadband system, a higher-transconductance tube was needed, and a much closer grid-to-cathode spacing was required. The spacing for the 175HQ tube was 0.024 inch, compared to 0.0055 inch for the 455A-F. The use of frame-type grids aided in maintaining the closer spacing. Table 3-3 compares the two tubes.

Table 3-3. Comparison of Submarine Cable Tubes

	175HQ	**455A-F**
Cathode temperature (true)	670°C	670°C
Cathode current density	0.7 mA/cm^2	10 mA/cm^2
Grid-cathode spacing	0.024 in.	0.0055 in.
Maximum element voltage	51 V	45 V
Transconductance	1000 μs	6000 μs

With the closer spacing, concern for small particles of debris in the tube structure was increased. To improve microscopic inspection for such unwanted particles, development engineers designed the tube with an open structure. Minimization of particle generation was effected by assembling the tubes under laminar flow hoods located in segregated clean rooms and by other advances in environmental control. This was the showplace clean room of its day.

As seen in Table 3-3, the cathode temperature was kept at 670 degrees C (true) but the current density was increased from 0.7 to 10 mA/cm^2. This was necessary to achieve higher transconductance but was considered reasonable in the light of long-time life tests. The choice of cathode material was again of prime importance. By this time, work by physical chemists had advanced the knowledge of cathode emission phenomena to the point where the use of specific materials could be recommended. Thus cathodes were made from selected melts of high-purity nickel to which had been added 2 percent of magnesium.

Once more, close attention was paid to the tungsten used for heaters, since the heaters, protected in a more refined way by gas tubes, would again be connected in series for the entire system. Control of materials, assembly, processing, aging, testing, and inspection were pursued to a high degree, and again all information was scrutinized in selecting individual tubes for system use.

The performance record of the 455A-F tubes was most impressive. As of November 1978, 5874 tubes in 10 cable systems had accumulated 738 million tube-hours of service. Two tubes were considered "probable failures," although no service interruption could be directly attributed to either tube.

The gas-tube surge protectors were made with the same conservative care. While they were not actively part of the repeaters, they provided standby protection and were required to perform over the same time period in the same remote locations.

Gas-filled bypass tubes were needed in each repeater as a part of the fault-locating arrangement. They were designed to break down in the event of an open circuit within the repeater, thereby restoring circuit continuity so that the remainder of the repeaters could continue operating. The tubes were also necessary to protect against transient surges that might propagate down the cable in the event of external damage to the cable sheath. Requirements for the bypass tubes were (1) the breakdown voltage must be safely above the normal operating voltage drop across the repeater; (2) when breakdown occurs as a result of an open circuit within the repeater, the tube must be able to carry the full cable current of 0.25 A with a sustaining voltage less than 20 V to minimize heat generation in the repeater; and (3) for surge protection, the tube must safely carry short-duration current pulses of either polarity measured in hundreds of amperes. An

argon-filled tube containing a cold cathode heated to emitting temperatures by ionic bombardment successfully met these requirements.[53,54]

VI. PICTUREPHONE VISUAL TELEPHONE SERVICE TUBES

Two of the last tubes developed by Bell Laboratories were used with experimental visual telephone service. The display tube used for this system was not the usual cathode ray tube.[55] [Fig. 3-38] It was a plug-in device requiring no adjustment during installation. It was encased in plastic and had a glass shield across its face to serve as protection against accidental implosion. The best technology of the time was used to achieve long-life coated powder cathodes. The cathodes were operated continuously at a slightly reduced temperature to allow "instant on."

The camera tube, developed by a group led by E. I. Gordon, was based on the conventional vidicon tube used in the 1964 World's Fair PICTUREPHONE visual telephone service sets. However, the experience at the Fair showed how vulnerable the antimony trisulphide image-sensing target was to accidental exposure to bright light. The effects ranged from burn-in of ghost images to local destruction of the target. To overcome this problem and to take advantage of integrated circuit technology, de-

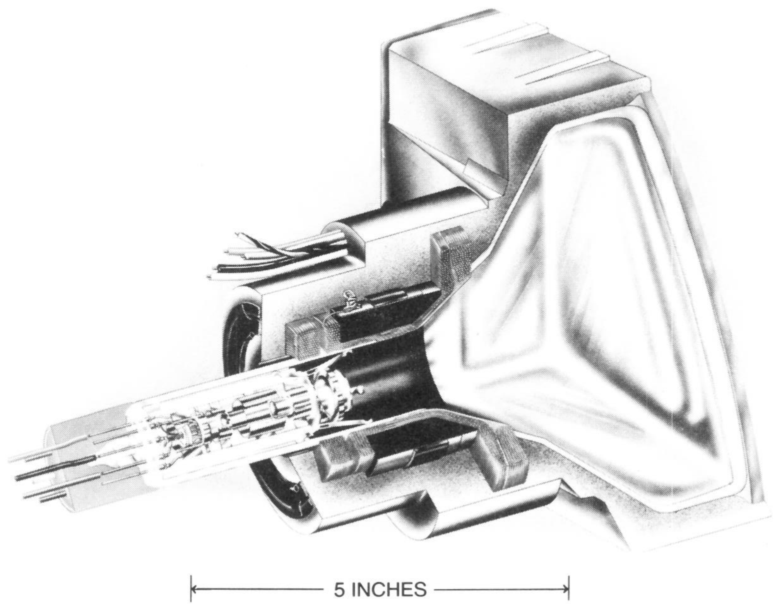


Fig. 3-38. The PICTUREPHONE visual telephone service display tube. Unlike entertainment television tubes, it required no adjustments. A glass shield in front and plastic encasement served as protection against accidental implosion.

velopers turned to the use of a silicon diode array containing upwards of 250,000 diodes on 20-micrometer centers. This concept was invented early in 1966 and by July 1966, feasibility had been established. The bright-light problem was solved; a camera tube with good sensitivity, especially in the near infrared, resulted.[56] [Fig. 3-39] An intense development effort involving Gordon's group at Murray Hill, New Jersey and a group under S. O. Ekstrand at Reading, Pennsylvania resulted in models for an experimental trial and Western Electric production during 1970.

In addition to use in PICTUREPHONE visual telephone service, this camera tube was used as the red channel of color cameras, and was used for surveillance in parking lots, apartment houses, etc. It also had important military applications. One version of it was used in the Apollo moon landing experiments. A storage tube version was used in luggage surveillance systems at airports.

VII. TUBES FOR ELECTRONIC SWITCHING SYSTEMS

Initial systems planning for a high-speed electronic switching system involved a central computer-type control using the high-speed and random-access storage capabilities of electron-beam deflection tubes. A semipermanent memory called the flying spot store, incorporating a cathode ray tube to access information stored on photographic plates, was also developed. Parallel readouts of this memory were obtained by the simultaneous interrogation of many photographic plates arranged in front of a single cathode ray tube. The system plan involved using the low-noise negative resistive characteristics of the hollow cathode gaseous discharge tube that had been under development for some time for the talking paths. Development of production tubes for the initial switching system trial at Morris, Illinois was begun in the early 1950s. (See another volume in this series subtitled *Switching Technology (1925-1975)*, Chapter 9.)

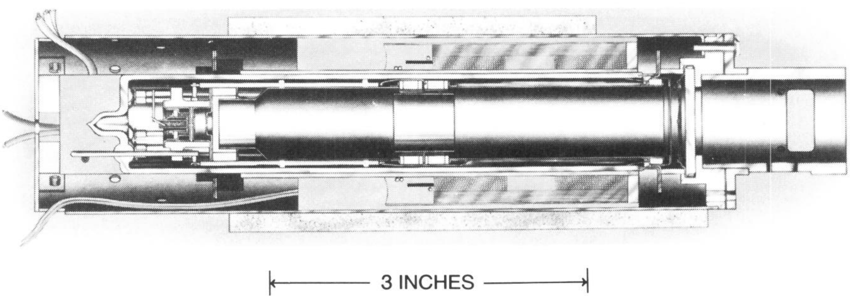


Fig. 3-39. Camera tube for the PICTUREPHONE visual telephone service system. It used a silicon diode array as the light-sensitive target to solve the bright-light problem, and was especially sensitive in the near infrared.

7.1 Barrier Grid Storage Tube

The barrier grid storage tube, A4004, used an electrostatically deflected electron beam to deposit charge on a dielectric surface (writing) and the same beam at a later time to detect and remove the charge (reading).[57] The basic structure of this tube is shown in Fig. 3-40. The control of secondary electrons produced when the electron beam strikes the surface is an important function in the charge and discharge. As shown in Fig. 3-41, a fine grid, acting as a barrier and adjacent to the flat dielectric surface, prevents the redistribution of secondary electrons from disturbing the charge on adjacent spots during writing and reading on any particular spot. The A4004 could store binary information on a square array of 128 by 128 elements—in modern parlance, a 16K random-access memory (RAM). The tube could write and read in less than 1 microsecond (μs) and was used in the Morris system at full capacity at a 2.5-μs storage cycle for both reading and writing.[58] Reading destroyed the charge (erased) and rewriting was required if the charge information was to be retained for subsequent use.

7.2 Cathode Ray Tube for Flying Spot Store

The design of the flying spot store for the semipermanent memory was based on the availability of a suitable cathode ray tube under development commercially. Unfortunately, that development fell far short of meeting the specialized requirements and had to be abandoned. Development was then undertaken in the electron device department to meet the desired requirements in time for the systems trial. [Fig. 3-42] Tube requirements included (1) negligible beam distortion with electrostatic deflection, (2) a phosphor screen with adequate life and fast decay after excitation, and (3) a nearly optically flat tube face without appreciable imperfections in the glass, which would interfere with the imaging of the individual light

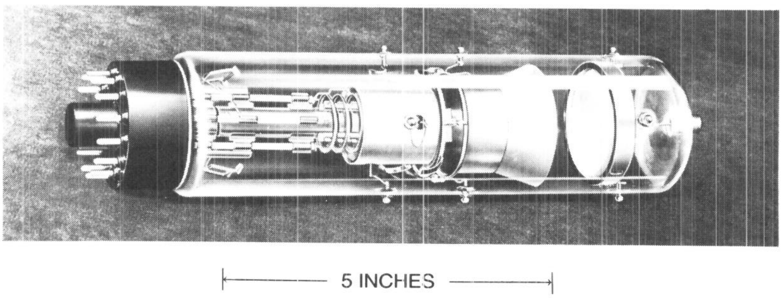


Fig. 3-40. The barrier grid storage tube used as a memory device in early field experiments with electronic telephone switching. An electron beam deposited information on a dielectric surface and also read information from the surface.

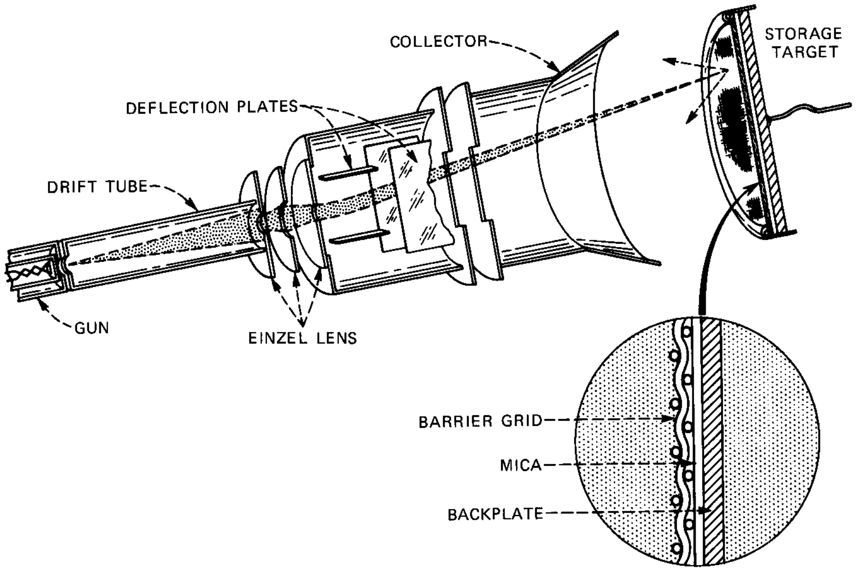


Fig. 3-41. Essential elements of the barrier grid tube. It was a 16K random access memory with a 2.5-μs read-write cycle time.

spots. Fortunately, production models of the cathode ray tube M2000 developed at the Murray Hill site met the necessary requirements and were installed in the Morris system trial.[59] The optical face plate for the tube was an interesting challenge. Glass manufacturers were not able to meet Bell Laboratories specifications for the 15-inch diameter, 3/4 inch-thick flat plate. The problem was occlusions in glass greater than 1 to 2 mils in diameter. It was solved by inspecting selected pieces of glass from two manufacturers until suitable areas could be found.

7.3 Talking Path Gas Tube

As discussed above in section 4.5, a hollow cathode structure was designed as part of a counting or stepping tube. Among the characteristics of interest were its low impedance to the transmission of audio frequency signals and its negative resistance for useful discharge currents.[60] These characteristics permitted the design of switching networks in which gas tubes replaced relay contacts in the talking path. [Fig. 3-43] These tubes took advantage of the stable discharge characteristics developed in the use of pure molybdenum cathodes.

The Morris field trial of an electronic switching system made extensive use of such unique gas diodes as electronic crosspoints in the switching matrix that provided connections through the system.[61] These tubes also

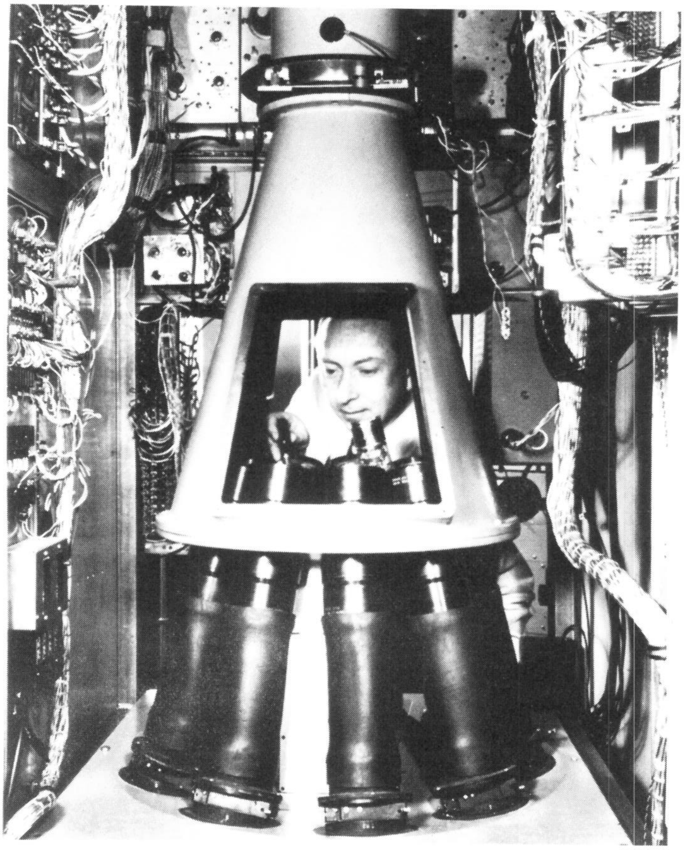


Fig. 3-42. Laboratory model of the flying spot store. Design objectives included minimum beam distortion, a phosphor screen with very fast decay, and a nearly optically perfect tube face.

provided other switching control functions because of their stability and current capacity.[62,63] (See *Switching Technology (1925-1975)*, Chapter 9, section 4.6.)

The gas tube crosspoint provided the switching function as a result of the difference between the breakdown voltage of 200 V and the discharge-sustaining voltage of 110 V. The residual free electrons in the gas needed to permit rapid breakdown were provided by an auxiliary photoelectric surface in the form of barium getter evaporated on the glass wall of the tube, activated by the illumination of fluorescent lamps in the network cabinets. After breakdown, the tube provided the talking path, the negative resistance furnishing a small amount of voice frequency amplification to offset other loss in the voice path.

For all applications, about 70,000 of these crosspoint diodes were re-

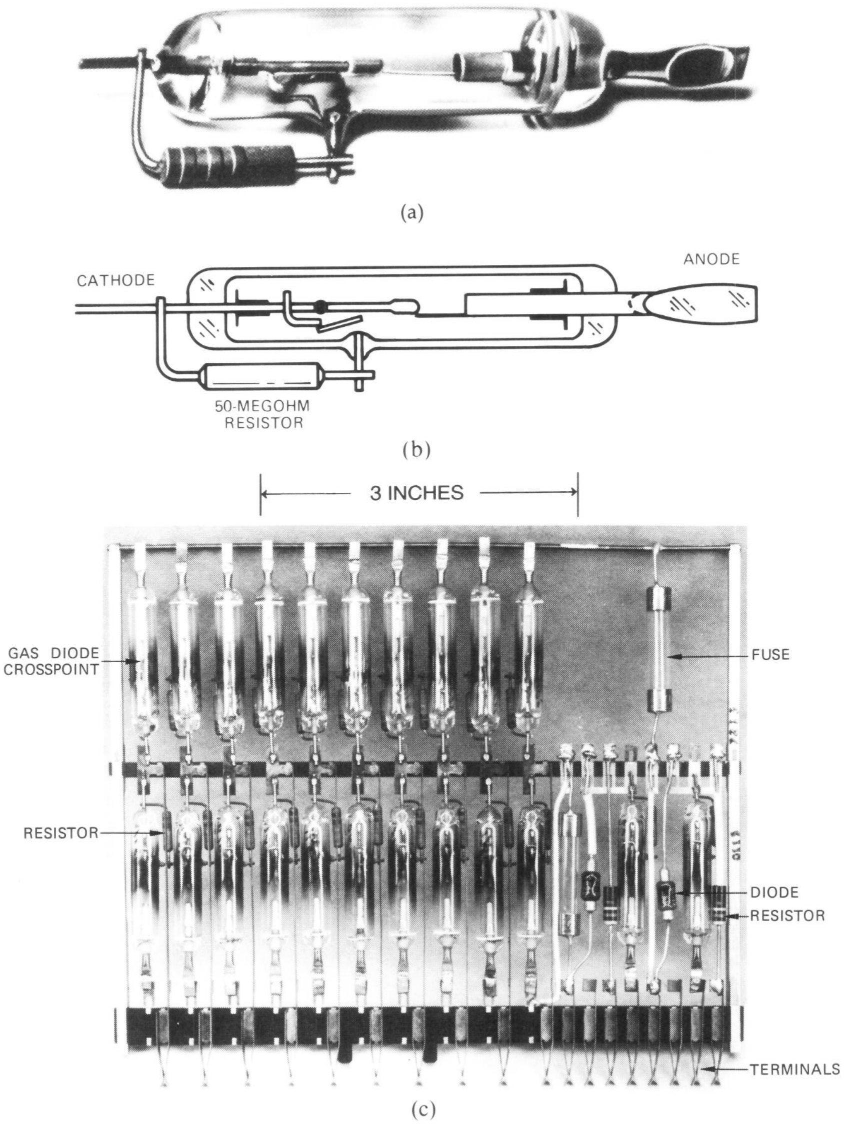


Fig. 3-43. Gas tubes for the talking path. (a) Gas tube crosspoint. (b) Schematic of gas tube crosspoint. (c) Plug-in network module for the Morris, Illinois field trial. In addition to its switching function, the device amplified voice signals. (Scale is for (c) only.)

quired for the Morris installation. Over 2000 other control tubes were also required to provide appropriate selection and latching of an available path through the network, and later to release the path. Most of these required the stability of the molybdenum cathode discharge for operation.

Thus the developed technology of the cold-cathode gas discharge provided the tools for initial study of the concepts of electronic switching, which would go forward from those years with the broadening technology of semiconductor devices.

VIII. EPILOGUE

It has been possible here to cover only the highlights of Bell Laboratories contributions to the electron tube art and science. Because of space limitations, many areas are discussed more briefly than they merit. These include magnetron improvement for aircraft and missile detection systems, reliability improvement in these systems, and TWTs for application in the hostile environment of missile guidance systems.

As semiconductor technology advanced, application of resources to electron tubes steadily declined so that, except for TWTs and the microwave triode, development activity by the late 1970s was negligible. Yet in 1974, Western Electric manufactured nearly 1,200,000 tubes to support equipment designed before and during the semiconductor era.

REFERENCES

1. M. J. Kelly, "The Manufacture of Vacuum Tubes," *Bell Lab. Rec.* **2** (June 1926), pp. 137-144.
2. W. Wilson, "Reducing the Cost of Electrons," *Bell Lab. Rec.* **3** (November 1926), pp. 69-71.
3. J. A. Becker, "The Role of Barium in Vacuum Tubes," *Bell Lab. Rec.* **9** (October 1930), pp. 54-58.
4. W. R. Ballard, "The High Vacuum Tube Comes Before the Supreme Court," *Bell Lab. Rec.* **9** (July 1931), pp. 513-516.
5. H. E. Mendenhall, "Radiation-Cooled Power Tubes for Radio Transmitters," *Bell Lab. Rec.* **11** (October 1932), pp. 30-36.
6. W. H. Doherty and O. W. Towner, "A 50 Kilowatt Broadcast Station Utilizing the Doherty Amplifier and Designed for Expansion to 500 Kilowatts," *Proc. IRE* **27** (September 1939), pp. 531-534.
7. Notes of an interview with J. O. McNally. [AT&T Bell Laboratories Archives Collection.]
8. J. W. Gewartowski and H. A. Watson, *Principles of Electron Tubes* (Princeton, New Jersey: D. Van Nostrand Co., 1965), p. 216.
9. C. E. Fay, "A New Vacuum Tube for Ultra High Frequencies," *Bell Lab. Rec.* **13** (August 1935), pp. 379-382.
10. M. J. Kelly and A. L. Samuel, "Vacuum Tubes as High Frequency Oscillators," *Bell Syst. Tech. J.* **14** (January 1935), pp. 97-134.
11. M. S. Glass, U. S. Patent No. 1,980,196; filed October 10, 1931; issued November 13, 1934.
12. M. S. Glass, U. S. Patent No. 2,139,678; filed October 10, 1936; issued December 13, 1938.
13. M. S. Glass, U. S. Patent No. 2,170,944; filed May 29, 1937; issued August 29, 1939.
14. M. S. Glass and D. Hale, U. S. Patent No. 2,268,194; filed December 2, 1939; issued December 30, 1941.
    S. O. Ekstrand, U. S. Patent No. 2,245,581; filed December 2, 1939; issued June 7, 1941.
15. J. B. Johnson, "A Movable-Screen Cathode Ray Tube," *Bell Lab. Rec.* **26** (May 1948), pp. 219-221.

16. C. H. Prescott, Jr. and M. J. Kelly, "The Caesium-Oxygen-Silver Photoelectric Cell," *Bell Syst. Tech. J.* **11** (July 1932), pp. 334-367.
17. M. J. Kelly, "The Caesium-Oxygen-Silver Photoelectric Cell," *Bell Lab. Rec.* **12** (October 1933), pp. 34-39.
18. M. Glass, U. S. Patent No. 2,414,099; filed April 2, 1942; issued January 14, 1947.
19. S. B. Ingram, "Cold-Cathode Gas-Filled Tubes as Circuit Elements," *Elec. Eng.* **58** (July 1939), pp. 342-346.
20. G. H. Rockwood, "Current Rating and Life of Cold-Cathode Tubes," *Elec. Eng.* **60** (September 1941), pp. 901-902.
21. J. R. Pierce, "Rectilinear Electron Flow in Beams," *J. Appl. Phys.* **11** (August 1940), pp. 548-554.
22. J. R. Pierce, *Theory and Design of Electron Beams* (New York: D. Van Nostrand Co., 1954).
23. G. T. Ford, "Midget Tubes for High Frequencies," *Bell Lab. Rec.* **22** (November 1944), pp. 605-609.
24. G. C. Dalman, "A New Miniature Double Triode," *Bell Lab. Rec.* **25** (September 1947), pp. 325-329.
25. R. H. Varian and S. F. Varian, "A High Frequency Oscillator and Amplifier," *J. Appl. Phys.* **10** (May 1939), pp. 321-327.
26. J. R. Pierce and W. G. Shepherd, "Reflex Oscillators," *Bell Syst. Tech. J.* **26** (July 1947), pp. 460-681; see also Bell Telephone Laboratories, *Radar Systems and Components* (New York: D. Van Nostrand Co., 1949), pp. 488-709.
27. J. B. Fisk, H. D. Hagstrum, and P. L. Hartman, "The Magnetron as a Generator of Centimeter Waves," *Bell Syst. Tech. J.* **25** (April 1946), pp. 167-348; see also Bell Telephone Laboratories, *Radar Systems and Components* (New York: D. Van Nostrand Co., 1949), pp. 56-152.
28. G. B. Collins, ed., *Radiation Laboratory Series: Microwave Magnetrons*, Vol. 6 (New York: McGraw-Hill, 1948), p. 497.
29. J. Feinstein and R. J. Collier, "A Magnetron Controlled by a Symmetrically-Coupled TE_{011} Mode Cavity," *Le Vide* **70** (July/August 1957), pp. 247-254.
30. R. J. Collier and J. Feinstein, U. S. Patent No. 2,854,603; filed May 23, 1955; issued September 30, 1958.
31. A. L. Samuel, J. W. Clark, and W. W. Mumford, "The Gas-Discharge Transmit-Receive Switch," in Bell Telephone Laboratories, *Radar Systems and Components* (New York: D. Van Nostrand Co., 1949), pp. 310-363.
32. K. C. Black, "Stevens Point and Minneapolis Linked by Coaxial System," *Bell Lab. Rec.* **20** (January 1942), pp. 127-132.
33. H. T. Friis, "Microwave Repeater Research," *Bell Syst. Tech. J.* **27** (April 1948), pp. 183-246.
34. A. C. Dickieson, "The TD-2 Story, From Research to Field Trial," *Bell Lab. Rec.* **45** (October 1967), pp. 283-289.
    A. C. Dickieson, "The TD-2 Story, Vacuum Tubes and Systems Engineering," *Bell Lab. Rec.* **45** (November 1967), pp. 325-331.
    A. C. Dickieson, "The TD-2 Story, Changing for the Future," *Bell Lab. Rec.* **45** (December 1967), pp. 356-363.
35. K. M. Olsen, "High-Purity Nickel," *Bell Lab. Rec.* **38** (February 1960), pp. 54-58.
36. J. J. Lander, H. E. Kern, and A. L. Beech, "Solubility and Diffusion Coefficient of Carbon in Nickel: Reaction Rates of Nickel-Carbon Alloys With Barium Oxide," *J. Appl. Phys.* **23** (December 1953), pp. 1305-1309.
37. H. E. Kern, "Research on Oxide-Coated Cathodes," *Bell Lab. Rec.* **38** (December 1960), pp. 451-456.
38. D. W. Maurer and C. M. Pleass, "The CPC: A Medium Current Density, High Reliability Cathode," *Bell Syst. Tech. J.* **46** (December 1967), pp. 2375-2404.
39. J. A. Morton, "A Microwave Triode For Radio Relay," *Bell Lab. Rec.* **27** (May 1949), pp. 166-170.

40. R. Kompfner, "The Traveling Wave-Tube as Amplifier at Microwaves," *Proc. IRE* **35** (February 1947), pp. 124-127.
41. J. P. Laico, H. L. McDowell, and C. R. Moster, "A Medium Power Traveling-Wave Tube For 6000-Mc Radio Relay," *Bell Syst. Tech. J.* **35** (November 1956), pp. 1285-1346.
42. J. E. Sterrett and H. Heffner, "The Design of Periodic Magnetic Focusing Structures," *IRE Trans. Electron Dev.* **ED-5** (January 1958), pp. 35-42.
43. C. E. Bradford and C. J. Waldron, "TH-3 Microwave Radio System: The Traveling-Wave Tube Amplifier," *Bell Syst. Tech. J.* **50** (September 1971), pp. 2223-2234.
44. M. G. Bodmer, J. P. Laico, E. G. Olsen, and A. T. Ross, "The Satellite Traveling-Wave Tube," *Bell Syst. Tech. J.* **42** (July 1963), pp. 1703-1748.
45. R. J. Collier, G. D. Helm, J. P. Laico, and K. M. Striny, "The Ground Station High-Power Traveling-Wave Tube," *Bell Syst. Tech. J.* **42** (July 1963), pp. 1829-1861.
46. G. T. Ford and E. J. Walsh, "The Development of Electron Tubes for a New Coaxial Transmission System," *Bell Syst. Tech. J.* **30** (October 1951), pp. 1103-1128.
47. R. F. Garrett, T. L. Tuffnell, and R. A. Waddell, "The L3 Coaxial System," *Bell Syst. Tech. J.* **32** (July 1953), pp. 969-1005.
48. M. A. Townsend, "Construction of Cold-Cathode Counting or Stepping Tubes," *Elec. Eng.* **69** (September 1950), pp. 810-813.
49. D. S. Peck, "Cold-Cathode Counting Tube," *Bell Lab. Rec.* **31** (April 1953), pp. 127-129.
50. "Two-Decade TAT-1 Record Called 'A Major Triumph,'" *Bell Labs News* (January 29, 1979), p. 3.
51. J. O. McNally, G. H. Metson, E. A. Veazie, and M. F. Holmes, "Electron Tubes for the Transatlantic Cable System," *Bell Syst. Tech. J.* **36** (January 1957), pp. 163-188.
52. V. L. Holdaway, W. Van Haste, and E. J. Walsh, "Electron Tubes for the SD Submarine Cable System," *Bell Syst. Tech. J.* **43** (July 1964), pp. 1311-1338.
53. T. F. Gleichmann, A. H. Lince, M. C. Wooley, and F. J. Braga, "Repeater Design for the North Atlantic Link," *Bell Syst. Tech. J.* **36** (January 1957), pp. 69-101.
54. J. O. McNally, "Early Tube and Cathode Work Leading to Submarine Cable Tubes." [AT&T Bell Laboratories Archives Collection: *Vacuum Tubes.*]
55. S. O. Ekstrand, "Devices—The Hardware of Progress," *Bell Lab. Rec.* **39** (May/June 1969), pp. 174-180.
56. E. I. Gordon, "A 'Solid-State' Electron Tube for the PICTUREPHONE Set," *Bell Lab. Rec.* **45** (June 1967), pp. 174-179.
57. M. E. Hines, M. Chruney, and J. A. McCarthy, "Digital Memory in Barrier-Grid Storage Tubes," *Bell Syst. Tech. J.* **34** (November 1955), pp. 1241-1264.
58. T. S. Greenwood and R. E. Staehler, "A High-Speed Barrier Grid Store," *Bell Syst. Tech. J.* **37** (September 1958), pp. 1195-1220.
59. C. W. Hoover, Jr., "An Experimental Flying-Spot-Store for Electronic Switching," *Bell Lab. Rec.* **37** (October 1959), pp. 366-372.
    C. W. Hoover, Jr., G. Haugk, and D. R. Herriott, "System Design of the Flying Spot Store," *Bell Syst. Tech. J.* **38** (March 1959), pp. 365-401.
    C. W. Hoover, Jr., R. E. Staehler, and R. W. Ketchledge, "Fundamental Concepts in the Design of the Flying Spot Store," *Bell Syst. Tech. J.* **37** (September 1958), pp. 1161-1194.
    M. B. Purvis, G. V. Deverall, and D. R. Herriott, "Optics and Photography in the Flying Spot Store," *Bell Syst. Tech. J.* **38** (March 1959), pp. 403-424.
60. M. A. Townsend and W. A. Depp, "Cold-Cathode Tubes for Transmission of Audio Frequency Signals," *Bell Syst. Tech. J.* **32** (November 1953), pp. 1371-1391.
61. A. D. White, "An Experimental Gas Diode Switch," *Bell Lab. Rec.* **36** (December 1958), pp. 446-449.
62. M. A. Townsend, "Cold Cathode Gas Tubes for Telephone Switching Systems," *Bell Syst. Tech. J.* **36** (May 1957), pp. 755-768.
63. K. S. Dunlap and R. L. Simms, Jr., "A Cold-Cathode Gas Tube Space-Division Network for an Electronic Telephone Switching System," paper presented at AIEE meeting, Morris, Illinois (October 1960).